A NEW GAME-BASED IMMERSIVE VIRTUAL LEARNING TOOL FOR PERCEIVING BEHAVIOUR OF STRUCTURES: STRUCTUREPUZZLEVR

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ABSTRACT

A NEW GAME-BASED IMMERSIVE VIRTUAL LEARNING TOOL FOR PERCEIVING BEHAVIOUR OF STRUCTURES: STRUCTUREPUZZLEVR

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It is widely accepted that virtual reality technologies will be used effectively used in architecture education as it is in other educations. However, according to the literature, there is a few examples of how immersive interactive virtual reality can be used in structural design education. StructurePuzzleVR is a game supported by digital game-based learning and surrounding-interactive virtual reality technology, designed to comprehend the behavior of structures under various situations by the help of simulations. In this way, an immersive virtual learning space is created in conjunction with design and learning activity. StructurePuzzleVR immerses students with as many senses as possible as three-dimensional motion, sound, touch and gravity simulations. Moreover, StructurePuzzleNotes is created as a written format of StructurePuzzleVR by isolating its immersive features. Thus, StructurePuzzleNotes is similar to the traditional structure education method used as a control group tool. Two groups of second year undergraduate architecture students are subjected to a pre-test consisting of long-span structure design questions. The groups are trained in different tools, then the post-tests are applied. According to SOLO Taxonomy evaluation, although the pre-results are in the same level, students who are taken to StructurePuzzleVR design more stable and various structures than the control group. Moreover, according to questionnaire; students who are taken into virtual reality education enjoyed more. The results show that an immersive virtual reality game can provide a concrete and meaningful experience in learning structural behaviors and designing structures, and show that this technology can be used more effectively in architectural education.

Keywords: Virtual Reality in Architecture, Digital Game-Based Learning in Architecture, Immersive Virtual Learning Environment, Structure Design Education, SOLO Taxonomy

ÖZ

YAPILARIN DAVRANIŞLARINI KAVRAMAK İÇİN OYUN TABANLI YENİ BİR ÇEVRELEYİCİ SANAL ÖĞRENME ARACI: STRUCTUREPUZZLEVR

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Yakın gelecekte sanal gerçeklik teknolojisinin çeşitli eğitimlerde olduğu kadar; mimarlık eğitiminde de etkin olarak kullanılacağı yaygın olarak kabul görmektedir. Fakat, incelenen literatürde çevreleyici interaktif sanal gerçekliğin mimarlık eğitimi özelinde strüktür tasarımında nasıl kullanılabileceğine dair etkili bir örnek bulunmamaktadır. Strüktürlerin çeşitli durumlar etkisindeki davranışlarını simülasyonlar yardımıyla öğrenciye daha iyi kavratabilmek; daha stabil ve çeşitli yapılar tasarlayabilmeleri için geniş açıklık geçen yapılar temel alınarak; tez kapsamında problem temelli öğrenme, dijital oyun tabanlı öğrenme ve çevreleyici-interaktif sanal gerçeklik teknolojisiyle desteklenen StructurePuzzleVR oyunu tasarlanmıştır. Bu sayede tasarım ve öğrenme faaliyeti birlikteliğinde bir çevreleyici sanal öğrenme mekanı oluşturulmuştur. StructurePuzzleVR üç boyutlu hareket, ses, dokunma, yerçekimi simülasyonlarıyla öğrencinin olabildiğince fazla duygusuna hitap ederek onu çevrelerken; oyunun tasarımında asıl rol oynayan bu çevreleyici özelliklerinden soyutlanıp kağıt üzerinde notlaştırılmasıyla sadece göze hitap eden StructurePuzzleNotes oluşturulmuştur. Böylece geleneksel strüktür eğitimi yöntemine benzetilen StructurePuzzleNotes deney kontrol grubu aracı olarak kullanılmıştır. İki grup ikinci sınıf mimarlık lisans öğrencisine geniş açıklık geçen strüktür tasarımı sorularından oluşan önce-testi uygulanmış, ayrı gruptaki öğrenciler belirtilen ayrı eğitim araçlarında eğitim almış, ardından sonra-testleri uygulanmıştır. Sonuçlar SOLO Taksonomisine dayalı bir rubrikte değerlendirilmiştir. Değerlendirmeye göre bütün öğrencilerin ilk test sonuçları aynı seviyelerde olmasına rağmen StructurePuzzleVR'a alınan öğrencilerin diğer gruptan çok daha stabil ve çeşitli strüktürler tasarladıkları, ayrıca yapılan ankete göre oyunlaştırılmış sanal gerçeklik eğitiminden çok daha fazla keyif alındığı gözlenmiştir. Aynı süreç iki mezun öğrenciye de uygulanmış ve aynı sonuçlarla karşılaşılmıştır. Sonuçlar çevreleyici bir sanal gerçeklik oyununun strüktürel davranışları öğrenme ve yapı tasarlama konusunda somut ve anlamlı bir deneyim sağlayabileceğini ortaya koymakta, bu teknolojinin mimarlık eğitiminde daha etkin kullanılmasının önünü açmaktadır.

Anahtar Kelimeler: Mimarlıkta Sanal Gerçeklik, Mimarlıkta Dijital Oyun-Tabanlı Öğrenme, Kapsayıcı Sanal Gerçeklik Öğrenme Ortamı, Strüktür Tasarım Eğitimi, SOLO Taksonomi

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LIST OF ABBREVIATIONS

ABBREVIATIONS	
2D	2 Dimensional
3D	3 Dimensional
AR	Augmented Reality
CAD	Computer Aided Drawing
CAVE	Cave Automatic Virtual Environment
DA	Diagnostic Assessment
DGBL	Digital Game-Based Learning
HMD	Head Mounted Display
IVE	Immersive Virtual Environment
IVLE	Immersive Virtual Learning Environment
IVR	Immersive Virtual Reality
P-##	Participant Number ##
PBL	Problem Based Learning
SPVR	StructurePuzzleVR
SPNotes	StructurePuzzleNotes
VE	Virtual Environment
VLE	Virtual Learning Environment
VR	Virtual Reality

CHAPTER 1

INTRODUCTION

1.1. Problem Statement

Increasing growth of computational resources and hardware power have made architecture education more innovative and feasible.

Although today various research topics related to building and material performance, mass-customization, smart environments, benefitting virtual learning environments are taking their place in curriculum of architecture education; there is not much change in structural education in architecture faculties.

As hardware power has been increasing, a challenge in the development of cyber-physical systems is also creating great differences in the design practice between the various engineering disciplines, such as software and mechanical engineering. Utilization of a cyber-physical system that simulates reality one by one and transfers it to the virtual environment can be produced as a solution to the problem of providing more quality structural design education.

As indicated, one of the important innovative development is through cyber-physicality is immersive virtual reality (IVR) environments. Since VR devices and applications are already in the market with a variety range of contents and prices; it makes these tools more appealing to use in education. Similarly, VR kits are also used in profession and education of architecture, such as for designing, understanding architectural spaces and visualization in architecture. The fast pace at technological advancements developed in the last decades have highly influenced and affected architectural practice and education. (Mendoza, Lopez, & Villamil, 2018) Design students will eventually embrace this technology in their design training. However, although it seems very beneficial to use VR in structure education, little is known about the possible practical results inferenced from usage of immersive IVR environment as a tool in structure education for architecture students.

Literature review focuses on two main subjects in order to reveal potentials of virtual reality in structural design education. First part is related to understand alignment between structural education practice in architecture faculties and major features of virtual reality technology. Second part researches on educational methodologies can be applied in VR medium and the ways of assessing educational improvements. Another necessity for analyzing these issues is to create a totally new educational medium rather than being an extrinsic addition to the existing educational design.

The research also elaborates on understanding results due to experiential differences between traditional education medium and educational virtual medium in terms of structural design product. Architectural design education is greatly associated with learning by experience and designing. This training needs synthesizing various types of knowledge and utilizing the knowledge in a creative manner to construct a product in a limited time. Therefore, experience, perception, intuition developed during the educational activities are important features through producing good quality architectural products, as well as for structure design. Regarding with that, a new educational IVR medium that provides more sensuous experience compared to less interactive traditional education by utilizing its technological key features as three-dimensional visualization, haptics, spatial audio and motion tracking can be researched upon. In terms of structural education, the thesis compares these two educational medium related to their provided experience of human-scale, dimension, understanding real-time physics, visualization, sound and motion.

In this context, potentials and the role of virtual reality medium should be explored in terms of its integration as a learning medium for learning how to develop intuition related to designing structures. In addition to that, implementation of the medium and assessment of its outcomes on learning process should be analyzed based on intended learning outcomes.

1.2. Hypothesis

This research hypothesizes that game based immersive virtual reality technologies can be utilized to improve novice architecture students' intuitive understanding of behaviors of structures.

1.3. Research Questions

The main purpose of this study is to make contribution to literature on the conception of immersive virtual reality learning environment and its relationship with structural design education through constructivist learning methodology. This study investigates potentials and the role of IVR application related to its methodological integration as a learning medium for learning how to design and develop an insight about basic notion related to structure design. Therefore, the following questions are to be explored:

- Can an interactive immersive virtual learning environment be more effective for teaching and learning organizations of structures than traditional and contemporary architectural education methods? Namely, is "Do and Learn" more effective than "Look and Learn"?
- Can VR's flexible ability to change time and space make structural education more dynamic, joyful and educative?
- Is this way of interactive learning in an immersive game environment allows students to generate different solutions to similar cases afterwards?
- What sort of educational assessment method or methods can be applied to measure and develop students' structural intuition?

In order to direct the expectations of reader and for clear understanding, brief outline of the thesis is given. Thesis is composed of five chapters, first chapter is introduction as it is stated, which involves and shows direction of the thesis. Second chapter is literature review to understand the current situation of structural design in architecture education and virtual reality technologies through virtual learning environments in architecture education. Third chapter synthesizes structural education and virtual learning environments and proposes an assessment method for if an immersive virtual learning environment is designed for structure education. Fourth chapter proposes a new immersive virtual learning environment and experiment for structure design. Eventually, in the fifth and the last chapter results of the experiment will be discussed.

CHAPTER 2

LITERATURE REVIEW

2.1. Structural Design in Architectural Education

Reviewing the literature of how sense of structure is taught and integrated within the curriculum of architecture education is needed in order to understand and infer a method of usage of innovative technologies such as, virtual reality tools in structural education.

Kamphoefner emphasizes that there has not been too much emphasis on structural knowledge in the architectural schools. A different approach in teaching structures to architectural students than engineering students has to be taken. Soft knowledge is oriented to architectonic sense, thus hard knowledge through soft methods should be facilitated. There is a gap that must be filled between the theory of structures and the art of teaching it to architectural students.(Emami & Buelow, 2016) Within the academy, structure and material courses are limited as teaching students as lecture-based sequence of physics, statics, strength of materials and structural analysis, as if calculation of forces offers as only means of understanding structures. However, other methods of teaching these subjects are mainly viewed as an exception rather than a rule. Moreover, these courses, often taught by engineers, struggle to reach their audience and isolate structures knowledge from the design studio. At its best, the topic reappears as an obligatory exercise in the comprehensive building project near the end of the program of study. As a consequence, structural design tends to become hard to learn task for the student and the professional.

2.2. The Contemporary Ways of Integration of Structure and Architectural Education

There are several methods to reinforce intuitive understanding analysis skills in teaching structural course to architecture students. Ilkovic (2014) lists two methodologies of teaching, namely PBL (Problem-Based Learning), and PPBL (Problem and Project Based Learning). In these methods, the teacher sets a problem in an assignment, which is solved by developing a project. Reviewing the literature, there are major sub PBL and PPBL techniques that can be used in addition to lectures, to teach structures to architecture students as:

- Hands-on activities in a lab-based environment, making physical models and structural testing of models.
- Computer-based simulation through structural analysis and interactive programs.
- Web-based interactive structural education.
- Integrating Structures within the design studio.

These techniques of teaching are later presented in the next section along with the case studies.

2.2.1. Hands-On Activities

Many educators think that theoretical lecture-based classes should be completed by other activities. Hands-on activities such as making physical models are one of them. While "most engineering education is auditory, abstract, deductive, passive, and sequential" (Felder & Silverman, 1988) built on the behaviorist tradition, the physical model in architecture education, serves as a visual or tactile means of concrete evidence, engaging the student in both actively dealing with and consciously reflecting positively his reasoning of structural intuition. Using physical models in structural education can cover a plenty of activities suggests several methods, namely *Metaphor* that relates examples from nature or common experience, *Analogy* which is to recall and relate, scaled case study models, scaled trial and error experimentation and full-scale prototypes. (Vrontissi, 2015) While Whitehead (2013) proposes haptic learning strategies by making students' use their bodies as if they are parts of structures in order to understand relation between force and form as a helper to develop structural sense of students. This learning method emphasizes that constructing relations between brain and muscle memory is useful for understanding and internalizing structural loads. In California Polytechnic State University, K'nex toys are used to build a 50-foot structure that will support a one-hundred-pound concrete panel as a term project. (Estes & Baltimore, 2014) This project relates how structure fits into the process of a large-scale structure course. Since K'nex toys are durable, easy to use and easily interchangeable compared to classical model preparation out of cardboard and concrete; students had not had to struggle with all these issues. Through the process they were able to try a variety of K'nex models. Reviewing the above survey, an array of methods in making physical models, from analogy to full-scale prototypes are used to reinforce architecture students' learning. Couple of key aspects such importance of haptic learning and importance of being easily producible models are highlighted in this section.

2.2.2. Computer-Based Simulation and Virtual Reality

Several tools have been developed that employ to provide structural performance feedback to the user. Some of these software systems is capable of providing real-time results including internal forces, reaction and sometimes required materials or costs. However, there are some limitations associated with these tools. First is that, student needs a long time to understand how to use the program, second is the software calculates the outcome as a black-box process so one cannot understand the process, another limitation is that these software systems are mainly designed for engineers and not for architects.

Virtual reality is another tool that can be used to teach structural concepts to future architects and engineers. Hereof, in 10 foot by 10-foot *CAVE* (Computer Assisted Virtual Environment) at the University of Michigan (Navvab, 2012) the students can observe how a steel structure bends or collapses from different perspectives in real-time. Observing this complexity one by one at the educational level can benefit students. (Sherif El-Tawil 2015)

2.2.3. Web-Based Educational Support and Interactive Education

Another teaching method in the digital age is using web sites, to share educational materials, as well as innovative teaching tool programs. Related to this, Vassigh (2005) refers to a project that creates a web-based environment for teaching and learning structures for architectural students. The project is involving three components as, "Interactive Structures Software (ISS)" which is a multimedia program, "Structures Learning Center" as a guide and finally "performance evaluation tool of the student". In addition, *eQUILIBRIUM* created by *BLOCK Research Group* (Pospišil, Vavrušková, & Vevrtátová, 2015) is another interactive online tool that illustrates graphic statics techniques by exercises, case studies, drawings and tutorials. Furthermore, *NovoEd* hosts a variety of online courses to teach Mechanics of Solids to students. To achieve one of the course's learning goals, online videos composed of worked-out problems are part of the course's pedagogical approach. (Fang, Adriaenssens, V Bands, & Segal, 2015) It seems that with student's wide access to the internet, online teaching materials provide a great platform for putting forward teaching concepts. Moreover, the fact that it is not bounded to a lecturer makes web-based education more practical, however if the intractability between program and the software is not sufficient to the expected outcome on the student would not be sufficient.

2.2.4. Integrating Structure into Design Studio

Many schools are aware of raising awareness of integrating structure in design studios is one of the most important features to change and deepen students' ability to creating different more quality of spatial sense, understand structural systems, material properties and form-finding. There are numerous examples for integrating structure and design studio. Relating to that, in University of Illinois first-year design studio tried to integrate with basic understanding of basic structures by using dynamic modelling techniques and large-scale installations to help students develop a visual and tacit structural intelligence, and to encourage students to take a greater interest in structural systems as a design concern. The main approach relies on hands-on experimentation with basic structural models and installations, and reveals the hidden potential of design in structural systems. (Wetzel, 2012) Another example is through the first-year summer internship of Middle East Technical University, the students are designing different quality of small and large scale of structures with different types of materials such as gypsum, resin, wood and steel. It is so natural that struggling with such variety of material to construct structures are in favor of students in their later architectural education and life.

2.3. The Terminology of Digital Space: Definition of Virtual and Physical

The term “virtual reality” is problematic in the sense that it implies that “virtual reality” is not real. Dictionaries define virtual reality as, “an artificial world that consists of images and sounds created by a computer and that is affected by the actions of a person who is experiencing it”. Although the term “virtual reality” technically includes non-immersive artificial worlds, it is currently understood to refer to the immersive artificial environments viewable through specialized headsets which allow a user to turn their head to look around and, to some extent, interact with the environment. In his research Ettlinger indicates that, part of what makes this term so catchy is that 'virtual reality' initially sounds like an oxymoron, which implies that 'virtual' is the opposite of 'reality'. However, he proposes that antonym of ‘virtual’ is ‘non-physical’ instead of real. (Ettlinger, 2007) In Merriam-Webster Dictionary ‘physical’ means, ‘relating to things perceived through the senses as opposed to the mind; tangible or concrete’.(‘virtual reality’, 2019) Ettlinger proposes a consistent view of what 'virtual' and 'virtual space' are by drawing an arbitrary line in the current fog of their multiple meanings through the concept of physical and non-physical. However, in the future developing projects such as Ultrahaptics will blur the boundaries between virtual and real. The project uses ultrasound technology so that the user could feel things in VR using his own fingers, moreover, another group is working on sensing smell while experiencing virtual space. (Takahashi, 2016) Another company tries to create new usage areas by implementing eye-tracking technology on a headset. Thus, non-physicality degree of ‘virtual’ is diminishing so the gap between real and virtual is narrowed down. With reference to this, in the near future it would not be surprising to come across with a term which integrates ‘virtual’ and ‘real’ in a semantically blurred way.

2.3.1. Induction of Reality into Simulation: Hyper-reality

The built environment and the relations composing it are becoming more digitized since the digital developments from 1980s. Nearly the same years, as Jean Baudrillard (1981) mentions that now the real is produced from miniaturized cells, memory banks, and it can be reproduced an indefinite number of times from these cyber-physical process as simulations. In fact, it is no longer really the real, because no imaginary envelops it anymore. It is a hyperreal, produced from a radiating synthesis of combinatory models in a hyperspace without atmosphere. Regarding that, according to a statistic in 2014, in the United States, people spend an average of 444 minutes every day looking at screens, equally 7.4 hours. That breaks down to 147 minutes spent watching TV, 103 minutes in front of a computer, 151 minutes on smartphones and 43 minutes with a tablet. At the top of the list Indonesia looking at screens for about 9 hours. (Epstein, 2014)

According to Baudrillard, there are four phases transiting into hyperreality. The first phase corresponds with developing indicators signs and images as a reflection of reality. In the second phase, signs had already decorated and exaggerate even warp the reality. However, since there is no absolute disengagement from reality, signs continue to reflect and symbolize the reality. Yet in the third and fourth signs and simulation replaces the reality and finally, a symbolic society emerges. This society is a simulacrum or imitation society in which symbols have no relation to the real ones, even human relations are only symbolic relations. (Güzel, 2015)

However, in the third group in which there is no distance between simulation and reality since the reality is absorbed by the simulation. It is an indication of this situation that the world's conquest is completed and extended because now the boundaries of reality are extended to infinity, however, the reality principle is wounded when the boundaries of the world are known. Baudrillard explains that spacey transcendence is the reality of saturation. It is now dead in science fiction and imagination, and the point reached is the age of hyperreality. It is no longer possible to speak of an epistemological truth or reality in this society that Baudrillard speaks of. Therefore, the only form of "being able to be seized" is now hyper-reality. (Baudrillard, 1981) Moreover, one of the reasons behind why he develops this concept is to express that the present world is not a real society and that the reality nor the place of truth is a virtual truth that takes the place of symbols, images and concrete. Namely, far from meeting the material need of people, the people prefer to have psychological satisfaction from hyperreality constructed by these images and symbols. (Güzel, 2015)

Therefore according to Baudrillard (1968) the use of technology, in the form of a fetishism, reverses the goal-instrument relationship that the human race has introduced with its technology; moreover, it is necessary to re-question whether there is an original rational relationship between goals and means in the field of technology and production in the society.

Another important area where simulation thinking will be applied is education. Baudrillard states that, education and educational research studies are also composed of series of simulations and discontinuities; these discontinuities are in themselves productive, not eliminable and help to contribute to the illusion of what education is, however they are not inclusive. (Moran & Kendall, 2009) Therefore, work of education is the simulation of education. Similarly, the same condition is valid for architectural education as well as the other education practices. In the educational simulations in architecture education such as design courses or other supporting courses; the fact that these courses are composed and designed on the pieces emerged from deconstruction of practice of architecture makes them successful in themselves, however it also makes them discontinuous part of discontinuous education lack of linkages. This discontinuity is resulted because of the fact that reality cannot be fully simulated into the education.

Today, parallel to Baudrillard's statement of re-questioning the use of virtual environments in terms of technology and production in society, numerous fields such as military, sport, mental health, medical training and education academics, engineers, educators are trying to develop virtual environments and make them usable other than gaming and entertainment field. The same advancements are also progressing in field of architecture education. It is that, today's computing power and images produced from these media cannot be distinguished from reality of built environment this improvement is giving designers to design the built environment connected to one's imagination as never before. Yet, as one will see in the next sections of literature view, major features of virtual reality is not integrated in architecture and structure education in terms of real-world problems. Usage of this technology in these fields is more limited with visualization and renderings. Because of this reason, relation between architecture and virtual environments has a danger of remaining as beautiful image fetishism as Baudrillard's stated as a form of fetishism. This thesis also touches on ways to make this relationship more useful and practical.

2.3.2. Historical Development of Virtual Reality

After 1950s and the new wave of technological advancements, brought about new visions of technologically-mediated immersive spatiality such as virtual reality. In 1955, Morton Heilig created *"Sensorama"* prototype which is a futuristic form of cinema composed of stereoscopic vision, spatial audio, smell and haptics (1992). Ivan Sutherland, developer of *Sketchpad* (1963) also developed the first Head Mounted Display (HMD) (1968) namely *"The Ultimate Display"* which can materialize *"Alice's Wonderland"* (1965). In 1987 name of "Virtual Reality" was coined by Jaron Lanier as an umbrella term. Lanier's company Visual Programming Lab (VPL) developed virtual reality gear as *Dataglove* and the *EyePhone* HMDs. They were the first company selling VR googles opens up a huge improvement in the area of virtual reality haptics. CAVE – presented in 1992. CAVE (CAVE Automatic Virtual Environment) is a virtual reality and scientific visualization system. (Mandal, 2013) Instead of using HMD it projects stereoscopic images on the walls of room to create an immersive environment. In 1993 *SEGA* invented *SEGA VR* headset and developed 4 games for the device. Although it was not a VR device in 1999 Wachowski's siblings film *The Matrix* hit the theatres. The characters that are living in a fully simulated world, with many completely unaware that they do not live in the real world. Although some previous films had dabbled in depicting virtual reality, such as Tron in 1982 and Lawnmower Man in 1992, *The Matrix* has a major cultural impact and brought the topic of simulated reality into the mainstream.('History of Virtual Reality', 2017)

However, most of these experimental approaches have disappeared from the field of architecture, with VR today used mainly as a simulation and evaluation platform, and overall as a representational virtual world are built for designers. In 21st century computer technology, especially small and powerful mobile technologies, depth sensors, motion controllers, and video game industry have exploded while prices are constantly driven down. Multiple consumer VR devices put on the market after 2015 such as *Oculus Rift*, *HTC Vive*, *Samsung Gear VR*, *Sony Playstation VR* that seem to finally answer the unfulfilled promises made by virtual reality in the 1990s will come to market at that time.

2.3.3. Cases of Virtual Reality in Architectural Design Education

Parallel to developments in VR tools in recent past, virtual reality (VR) re-emerged as an affordable technology providing new potentials for virtual learning environments (VLE) and use of VR in academics and education area started to be discussed again recently. Field of architectural education was also one of these academic fields. After 2000s virtual reality in architectural education put on the table majorly in the frame of modelling, designing, collaboration, representation and spatial perception.

In the area of VR as a modelling and designing tool, HoloSketch was an early development tool for sketching within a virtual 3D space. (Deering, 1995) DDDoolz modificates the design by dragging sets of cubes, resulting in the creation or deletion of new cubes and explored the use of VR in early design stages. (Achten, De Vries, & Jessurun, 2000) Additionally, "vSpline" which is an immersive virtual reality NURBS curve-based modelling software explores the potential of designing structures in virtual reality from the view of first person and explores the relations between physical design output and virtual design output in terms of scale. (Arnowitz, Morse, & Greenberg, 2017)

Virtual Reality is also lending itself to design collaboration in learning, teaching and communication of design ideas among architecture students, design professionals and clients during the early phases of design. Namely, another significant quality of VR is to assisting collaborative design process. The software named JCAD-VR flexible immersive and non-immersive environment for collaborative design provides different users to share and discuss design solutions by the help of freely sketched 3D objects in the same virtual environment. (Petric, Ucelli, & Conti, 2003)

There are also other researches that VR is used as a tool in representation and spatial perception. One of them is using VR to model buildings can be a step into the preservation of historical architectural values, allowing a type of immortalization of characteristics of buildings. To illustrate, a virtual project which visualize and animate measured architectural and construction details of 16th Century Suleymaniye Complex in Istanbul Turkey, while the animation and storyboard integrates link between the social structure of the city with the overall architecture and planning of the complex; virtual reality and animation tools were used through the process of analyzing the architecture and construction technology. (Ibrahim et al., 2007)

Another paper uses eye tracking technology in combination with questionnaires, a case study of an architectural space is explored in physical reality, virtual reality, 3D BIM model and finally through representation of the space in 2D plan and section drawings. As a result, the paper suggests that virtual reality can simulate a physical scenario to a degree where human behavior shows correspondences than experience of the same space through traditional plan and section drawings. (Hermund, Klint, & Bundgaard, n.d.)

2.4. Integration of Virtual Learning Environments into Structural Education for Architecture Students

As it is stated, structure education and architecture education have already integrated in many ways. However, naturally every method has its own misfit/s in terms of composing a base for fundamental structural concepts. For example, hands-on activities could need more time to prepare the required material and construct the structure. Moreover, generally it cost more than the others. Secondly, lecture-based static courses are mainly teacher oriented, remained on a flat surface in the form of sketches, calculations and slide shows on blackboard, as a result it lacks of interactivity and feedback. Thirdly, according to the literature, there is no computer simulation and virtual reality application has been created by using distinguished and superior features of virtual reality environment (VLE) on other methods, which are immersivity, haptics and sound. At last, web based educational support lacks of immersivity and interactivity.

2.4.1. Definition of Learning Environment, Virtual Learning Environment and Immersive Virtual Learning Environment

This thesis proposes a new immersive virtual learning environment (IVLE) by understanding advantages of immersive virtual environments over other mediums and by reinterpreting all the flaws of other methods. While building a new method through the research, it is essential to understand the basic notions behind the concepts of learning environment, immersive virtual learning environment and pedagogical approaches related to these settings.

Initially, concept of “learning environment” (LE), “virtual learning environment” (VLE) and “immersive virtual learning environment” (IVLE) will be explained respectively. Following these, to detail the subject, key components of IVLE and the advantages of IVLE over other mediums will be clarified.

A learning environment is a medium where participants can use resources to make sense out of things and build up meaningful solutions to problems. The simplest learning environment contains a learner, and a "setting" or "space" wherein the learner is using tools, acting, collecting and utilizing information can be with others. (Wilson, 1996) According to Perkins (1991) there are five key components common in every learning environments including traditional classrooms. These are *information banks, symbol pads, phenomenaria, construction kits* and *task managers*. These concepts will be explained and touched upon later in the thesis while synthesizing and systematization of IVLE for structure education.

Furthermore, various types of virtual environments (VE) have been used in different disciplines. These types are based on online or offline, single user or multiuser, non-immersive or in different levels of immersion. While some of these virtual environments are used in video game industry such as Second Life, Active Worlds and Lego Universe; some of these VEs are used only for educational purpose, called as virtual learning environment (VLE).

Virtual learning environment is software based designed information space to support teachers and students in the management of educational courses. These virtual systems allows following student's progress, collaboration and communication tools. (Cartelli & Palma, 2009) The representation of VLEs ranges from text based interfaces to most complex graphical output such as, animation, graphics, video-based asynchronous and synchronous tools such as e-mail, chat, forums, blogs, wikis, micro worlds, simulations, 3D open virtual worlds which provide communication between teachers and students. (Bri, García, Coll, & Lloret, 2009) However the key point is not the representation, but what the learners are able to do with this representation. (Dillenbourg, Mendelsohn, & Jermann, 1999) One of the major advantages of VLE's over traditional learning environments is that, learning tools included in VLEs are able to interact with other services. Then teachers or instructional designers populate the VLE with numerous resources including instructions, feedbacks, learning tools, case studies, documents etc. After that, all of these sources can be utilized as key components of learning scenarios. (Durand & Martel, 2006)

According to Schroeder an IVLE can be defined as, a computer generated display that permits the user or users to have a sense of being present in an environment other than the one they are actually in, and to interact with that environment. (Schroeder, 1996) IVLEs comes with plenty of promise of sensory information-rich learning experiences that enables wider scope of experiential learning in fully virtual spaces, computer desktops, augmented reality spaces, digital installations and mobile projective devices. Although, there are high number of IVE based games and educational applications have been designed since 1990s, due to the costs associated with the computational power and equipment the developments were interrupted. By the technological developments in that area; IVE games have attracted millions of people throughout the world in the 2010s. It is therefore not surprising to see large numbers of educators are aiming to integrate this technology into curriculums. (Van Eck, 2006)

The perceptual possibilities of 3D immersions with three dimensional visualization, motion tracking, haptics and spatial audio provides a much wider range of learning medium than has been achievable in the past. (Shalin, 2011) By explaining these features the possibilities of IVLEs will be narrated.

2.4.2. Three-Dimensional Visualization

Today a typical IVR system sends stereoscopic vision that is updated as a function of head tracking, possibly directional audio and sometimes some type of limited haptic interface. In a head-mounted display (HMD), the displays are mounted close to the eyes and head tracking ensures that the left and right images are updated according to the head movements of the participant with respect to the underlying virtual environment. The synchronized left and right images for each eye creates stereo vision. The participant has the illusion of moving, flying, changing between scenes in a second in three-dimensional environment that involves static and dynamic objects. Moreover if an IVR is an online-based and open to collaborations; it even can include avatar representations of other people. IVE's enhanced spatial knowledge representation provides greater opportunity for experiential learning, increased motivation and engagement, improved contextualisation of learning and richer effective collaborative learning as compared to tasks made possible by 2-D alternatives. (Dalgarno & Lee, 2010) Thanks to immersive realistic views provided by IVLEs, it is therefore not surprising to see that there are plenty of sectors such as medicine, space simulations, construction simulations, psychological tests, chemical and physics laboratories are designed in IVLE's.

2.4.3. Motion Tracking

In an IVLE, intuitive interaction is highly important when accomplishing a task. Traditionally, user controls "the avatar" through keyboard, mouse or gamepad. However, IVLE provides motion tracking technology which sensors are locating and sensing movements of head, hands, legs and torso, which is important while situating the one in the environment of IVLE and so to allows user to interact with the objects. Computer graphic systems use motion trackers for several primary purposes. These are, view control to provide position and orientation control; navigating user to a tracked wand to fly in a particular direction; object selection and manipulation which are provided by tracked handheld devices and lastly avatar animation by generating realistic movement through full body motion capture for human actors and other objects. Motion tracking is needed to create more realistic first-person real-world experience especially for the simulations. Different than keyboard and mouse controllers which constructs more bulky relation between cognition and the space, motion trackers are working as if they are natural body extensions of students and aid them to develop muscle memory. Therefore, in some cases utilizing motion trackers is more beneficial.

2.4.4. Haptic Technologies

In definition “Haptics” means both force feedback (simulating object hardness, weight, and inertia) and tactile feedback to illustrate with simulating surface contact geometry, smoothness, slippage and temperature. (Burdea, 1999) Today’s virtual environments are capable of simulating visual and physical realism to a very high level. Haptics technology provides an approach to realistic interaction in VEs. Force provided by haptics technology can help learners feel and understand the behavior of virtual objects better by supplementing visual and auditory cues and creating an improved sense of presence in the virtual environment. (Coutee & Bras, 2004). In an IVLE participants are able to interact and change the entities in the environment. For example, if at least one hand is tracked, then the participant can grab objects and move them to different locations, or carry out a variety of other types of interaction such as bending, breaking, teleporting through environment. Physics-based methods that are capable of maintaining high update rates are generally used for implementing haptic feedback in virtual assembly structure simulations. Researches has shown that the addition of haptics to virtual environments can contribute to improvement of students efficiency. (Seth, Vance, & Oliver, 2011)

2.4.5. Spatial Audio

Spatial audio can be used to direct the user’s attention and enhance the realism of the virtual experience by providing various directional and distance sound effects (Bormann, 2005). Use of spatial audio just as 3D visualization, haptics and motion tracking lead to the achievement of a greater sense of presence in an IVLE. When multiple numbers of users, distributed in 3D VLEs, including massively multiplayer online games and virtual worlds, it allows geographically dispersed users to explore an environment concurrently, with each represented by a surrogate persona or avatar visible to other users and with tools allowing text-based or audio communication.

2.5. Learning Theories and Methods in Immersive Virtual Learning Environments

In this part, educational theories and strategies commonly issued in the literature regarding theoretical or experimental studies on IVLEs are explored. According to literature review, constructivist theories such as experiential, problem-based, situated and game-based learning have the dominance among others.

2.5.1. Constructivist Theory

According to many scholars who have studied learning is that the body provides sensorimotor interaction with the environment as a mediation element. (Aiello, D'Elia, Di Tore, & Sibilio, 2012) Parallel with that, immersive virtual learning environments allow learner to bodily interactions, move in three-dimensional virtual environment that provides visual, auditory, haptic and kinesthetics feedback in real-time. Therefore, a constructivist point of view supports the potential of an "invented reality" as virtual reality environment., strongly influenced by the individual's capacity for perception and action. (von Glasersfeld, 1984) Based on the premise that we all construct our own perspective of the world through individual experiences; constructivism centers preparing the learner to problem solve in unclear situations. (Schuman, 1996) Namely, constructivism indicates the idea that learners construct knowledge for themselves each learner individually and socially constructs meaning as he or she learns.(Hein, 1991)

The constructivist theory opens new perspectives for teaching through the use of IVLEs, considering the unseparable bond between the learning processes and their learning environment in which the interactions essential for successful learning. (Aiello, D'Elia, Di Tore, & Sibilio, 2012) Moreover, according to the perspective proposed by Jonassen (1991) it seems that IVLE and constructivist learning environments has more in common. Jonassen's principles related to constructivist learning environments are as, they should avoid reflect complexity of reality as much as possible, they should provide cases more than predetermined instructional sequences, they should offer multiple representations of reality, they should support the construction of knowledge with the learning environment.

2.5.2. Problem Based Learning

Problem-based learning (PBL) is a type of learner-centered educational approach where students learn a subject through their experience in solving open-ended problems. (Abdullah, Mohd-Isa, & Samsudin, 2019) PBL begins with the assumption that there can be more than one right answer. Finding creative solutions to a problem or a driving question is what makes the learning meaningful and lasting, and also difficult to evaluate from a traditional standpoint. The main principle of PBL is based on maximizing learning activity with investigation, explanation and resolution by starting from real-life problems. (Ünver & Ayşe, 2011) In PBL, student has control all over the problem, in addition to that learning attitudes such as, critical thinking, self-directed learning, reasoning and planning the process are important features as outcomes. (Kwan, 2015)

A VLE can simulate a real-world problem within a digital environment. A well-designed VLE application that employs PBL methodology can provide opportunity for learners to explore the structure of a problem, construct new knowledge by interacting with the key features of virtual reality such as immersion, haptics and spatial sound as it is in real life. In addition to that, motivation and cognitive load are also highly issued in virtual learning environment studies. Motivation is a major factor in learning process. (Sutcliffe, 2003) As an example related with motivation and VLEs, Limnou's study shows that compared to a two-dimensional environment, an immersive 3D VLE can increase students' motivation and enthusiasm due to its real-life resembling characteristics. (2008) Furthermore, a realistic and immersive VLE is able diminish cognitive load during the learning process, and therefore it provides knowledge acquisition with less of a cognitive effort compared to traditional educational methods. (Chittaro & Ranon, 2007)

2.5.3. Situated Learning

Situated learning is an approach that in which learning occurs in meaningful and realistic contexts where the learning material will be applied in the future within a social environment.(Shalin, 2011) When students are trained in such an environment, they benefit not only from the learning material but also from the culture in that environment, such as the vocabulary used, and the behavior related with that world. Creating highly realistic and immersive environments is something that digital games do particularly well. (Prensky, 2001)

2.5.4. Game Based Learning

Game-based learning (GBL) describes a medium where game content and game play develop knowledge and skills acquisition, and where game activities involve problem-solving spaces and challenges that provide learners with a sense of achievement. (McFarlane, Sparrowhawk, & Heald, 2002)

The importance of GBL is increasing through the years. Skills relevant to the 21st Century are significantly different from skills the educational system currently values. (Sqire, 2005). Contemporary learning and innovative skills are more defined as critical thinking, creativity, collaboration and communication. (Binkley et al., 2011) While critical thinking skills include scientific reasoning, problem solving and computational thinking; creativity includes innovative thinking and the ability to see failure as an opportunity for improvement; collaboration emphasizes the ability work effectively with diverse teams; communication underlines importance of articulating variety of thoughts in a variety of forms in diverse environments. (Doleck, Bazelais, Lemay, Saxena, & Basnet, 2017) However, traditional education embanks creativity by only one correct answer and tends to have standardization and conformity. (Plucker & Makel, 2010) Moreover, it is hard to evaluate 21st Century skills by standardized traditional assessment methods such as multiple choice tests and oral exam. In contrast, games are able to provide a method for assessing these hard to evaluate skills.(Shute, 2011) Various studies have argued that games are able to increase learning motivation provided by multi-sensory tasking and develop cognitive, sensory and motor skills.(Garris, Ahlers, & Driskell, 2002; Prensky, 2001) GBL has been tested in military, medical, business and physical training, using different types as role-play, simulation and digital games; these tools give learners ability to imagine new possibilities in a real situation and recognize the feedback from the reaction. (OO & Lim, 2015)

2.5.5. Digital Game Based Learning

Prensky (2001) defines digital game-based learning (DGBL) as the combination of "computer video games with a wide variety of educational content" to achieve outcomes no worse than traditional content-centric instruction. Moreover, he states that there are three key reasons why DGBL is important and more preferable. These are, firstly DGBL meets the needs of today's and the future's generation of learners. Furthermore, according to many DGBL experts the real power of digital games lies under ability to promote 21st Century skills. (Van Eck, 2015) Second reason is that, DGBL is motivating because it is fun. And lastly, it is enourmously versatile, adaptable to almost any subject, information, required skills and very useful when used correctly. According to a meta-analysis, a well-designed DGBL game improves learning by 7 to 40 per cent.(Laham et al., 2009) Rather than being "fun" and "tricking" students into learning, potential of having supported by powerful learning strategies such as situated learning, authentic environments, optimized challenge and support make DGBL more effective learning tool. (Van Eck, 2006)

2.5.6. Digital Game Based Learning and Architecture

In addition to being tested in various disciplines, DGBL has also gained a momentum in educational approaches in architecture. To understand the relation between DGBL and architecture education the similarities has to be considered. As Van Eck (2015) stated, one of the main similarity between DGBL and architecture education is that both are problem-based learning subjects. Similarly, project-based education in architecture, one of the most utilized methods in architecture was first implemented in

Ecole des Beaux Arts, which experienced problem and solution integrated design. After that, the Bauhaus school had implemented this educational approach by aiming to increase students' creativity and personal expression by freeing them from all kinds of conditioning. (Taşçı, 2016) Some of the other similarities are that both are based on problem solving such as requiring intuitional aspects, presence of contradictions, uncertainties, having flexible structures that can be orientated by the individual and they have dependence on some certain general rules. (Taşçı, 2016)

Today, the architecture studio education is conducted by the same traditional tools since Bauhaus, which are face-to-face interviews, drawings, making models and group works. As the huge technological improvements have changed the architecture since the Ecole des Beaux-Arts era until our time, as Prensky asserted, the education systems and the learning processes of the learners should be revised correspondingly; by considering that the minds and perception structures of the students who have been born into technology, have changed too. (Prensky, 2001)

Considering these inputs, utilization of digital games as a tool can be a promising answer in architecture education. Compared to other methods of teaching, well-designed digital games provide many advantages. For example, DGBL applications develop "mental rotation and spatial skills" (Çubukçu, Çubukçu, & Nasar, 2006); they increase "visual attention" to a considerable level (Green & Bavelier, 2003), provide problem-solving skills, ensure complete motivation and participation. In addition, digital games are generally and more responsive, can do easily simulating physics by combining all the parameters, capable of more, better and various graphic representations, can provide virtual environments shared by multi number of players at any time, can generate and modify huge numbers of options and scenarios, can be updated instantly. (Prensky, 2001)

Furthermore, digital games are utilized in architecture education recently, in many disciplines as cultural heritage education (Antiqueira, Antiqueira, & Vizioli, 2015), construction management (OO & Lim, 2015), for understanding special qualities of architectural space and as a collaborative design tool. To illustrate, a research done by Şahbaz and Özköse (2018) proposes that DGBL can be used in order to raise an awareness about value of historical buildings. The scenario of the game is a basic puzzle-solving scenario. Three students enter a historical bathhouse, after a while, the students are stucked in the building. While escaping from the building, research anticipates that students will be more cautious and look deeper in details of the historical bathhouse. The experiment reveales that providing students the opportunity to play by interactive media tools enriches and broadens scope of activity and thinking. Another experiment is implementation of immersive simulation studios into architectural design of spaces. (Angulo & Velasco, 2014) After the students walk through and try to sense characteristics of a lobby in VE, they are expected to guess the dimensions and redesign it in a 3D modelling software. Even though the experiment provides minimum interaction between space and the student, the virtual space used as a digital based learning space. After the study, majority of the students agreed that VR can be a useful tool in architecture education. In addition to these, another study (Kathryn & Ning, 2011) defines *Lego Universe* game as a tool which can move beyond game as a design tool in colaborative environments. *Lego Universe* is a game which allows people to build structures and all sort of things can be buildable. The research emphasizes that to better facilitate collective design in the game, various tutorial tools in the form of DGBL to assist participants in learning how to design and collaboration skills at their levels has to be provided, namely by understanding whole game as a learning environment.

Although DGBL can be very useful for different branches of architectural education, literature shows that usage of DGBL in architectural education is limited for now. This can be because of not grasping importance of DGBL in architecture or being hard to develop games by teachers because of complicated usage of game engines. (Van Eck, 2015) However, game engines as Unreal Engine and Unity 3D allow users to build digital games easily by the help of numerous assets in open source library and tutorials.

Therefore, not internalizing importance of DGBL seems more powerful than the other reason.

One of the promising branch of architectural education which can be taught by the help of immersive DGBL is structural education. However, in the literature there is no interactive DGBL environment related to structure education can be found. As seen in the literature review in this thesis, PBL is very useful while teaching structural behaviours to students and, similarly, DGBL has the potential to be powerful problem-based, authentic, and collaborative learning environments. (Whitton, 2014) Hence, design of structure can be experienced on problem solving activity based digital game based learning environment. As a result, this thesis can contribute to literature by designing a game which synthesis DGBL, architecture education and structure education as teaching fundamentals of statics and designing structure design problem.

2.6. Elements of Game Based Learning

To design an IVLE the characteristics of GBL should be understood first. At the core of GBL game elements are standing. These are defined as a set of building blocks or features shared by games, also named as characteristics of games. (Bhatia & Ryan, 2018) However, since there has not been a consensus on the characteristics of games authors have suggested various game characteristics to make them as engaging educational tools. Although most elements are common to many games, there are slight differences between them because of the authentic discipline they are used in. Some game element taxonomies are more theoretical some are more conceptualized and concrete. For example, Deterding et al. (2011) determined game elements for media research as game interface design patterns, game design patterns and mechanics, game design principles and heuristics, game models and game design methods. Another research done by Floryan (2009) states that game elements for computer science related GBLE are as, goals, content and user tasks, simulation fidelity and user freedom. As the examples show, the taxonomies of game elements vary according to discipline from which they stem and what they include. Shute and

Ke (2012) identifies the elements as, interactive problem solving, specific goals/rules, adaptive challenge, control ongoing feedback, uncertainty and sensory stimuli.

However, Prensky's (2001) definition of game elements are more appropriate for designing an IVLE for basic structure education in terms of being general so to provide flexibility and being detailed so to indicate the research better. Prensky's game element taxonomy involves rules, goals and objectives, outcomes, feedback, conflict (competition, challenge, opposition), interaction and representation (story).

The next chapter will elaborate on designing an IVLE game for structure education in the by the help of game element's taxonomy and synthesizing all the literature review up to now.

2.6.1. Rules

A game without rules is not a game it is a play, rules are the entities which makes game an organized-play. (Prensky, 2001) Rules impose limits by helping player to focus on specific features. (Shute & Ke, 2012) Namely, rules force player to take specific paths to reach goals and ensure that all players take the same paths and stop player cheating. Moreover, strategic selection of moves or actions within a game should be flexible to allow the game activity to evolve based on player styles, strategies, previous experience and other factors. (Crookall & Arai, 1995)

2.6.2. Goals and Objectives

One of the strong findings in the literature on motivation is that clear, specific and respectively difficult goals lead to enhanced performance. (Locke & Latham, 1990) In a game, achieving goals is a major part what motivates the player. Furthermore, goals and objectives provide learners a scale measurement whether they are successful or not. The goal is often stated at the beginning of the rules; for example, goal can be getting the highest score, reaching the end, beating the big boss, capturing the flag, constructing a stable bridge and so on. (Prensky, 2001) Goals in game can be implicit, explicit or they can be open goals which player can set for himself through the game like Sim City or Minecraft.

2.6.3. Outcomes and Feedback

In classic games there are two endings as winning or losing. Conversely, in an educational game the outcome can be increasing level of learning as much as possible. Feedback gains importance when teachers wants to maximize learning outcome. Learning takes place by the timely given feedback in a game. (Prensky, 2001) Therefore, DGBL environments should provide timely information to players about their performance. (Shute & Ke, 2012) Moreover, even in commercial games there is a great amount of continuous learning goes on. The player is learning constantly how the game works, what the designer's underlying model is, how to succeed, how to level up and win. As a result, in order to keep learner motivated and sustaining learning through the game immediate feedback has to be given. Feedback can be actively given as instructions by the teacher or can be in form of numerical scores, texts, graphics. In addition to that, failure situations can be designed to give feedback. Namely, rather than describing the failure as an undesirable outcome, failure can be designed an expected occasion by the teacher and sometimes even necessary step in the learning process. (Kapur & Bielaczyc, 2012) They also provide opportunities for self-regulated learning during the game, where the learners tries to fulfill strategies to reach the goal, monitoring of the task and assessment of the effectiveness of the strategies used to achieve the intended goal. (Barab, Warren, & Ingram-Goble, 2008)

2.6.4. Conflict, Competition, Challenge and Opposition

Prensky (2001) states that conflict, competition, challenge and opposition are the problems that player tries to solve. The degree and type of challenge has a great importance on the motivation of learner. According to Malone and Lepper (1987) individuals desire an optimal level of challenge, that is, if challenges are too difficult to be handled by the students, on the other hand if challenges are too easy that the participant can get bored and can lose their motivation. Moreover, there are several ways when optimal level of challenge wanted to be obtained. Game should employ progressive difficulty levels, multiple goals and certain amount of implicit goals to ensure an uncertain outcome and provide space for creativity. (Garris et al., 2002) If outcome of the game can be seen as predictable, it will lose its appeal so game fails. (Shute & Ke, 2012) However, not everybody likes to have an opponent or conflict or vice versa. To cope with that, games can be treated as authenticated designed spaces according to various types of students. For example, a single player puzzle game can also be a challenging game or in some situations applying player versus player methodology in a game can be more beneficial.

2.6.5. Interaction

One of the most frequently cited reasons to consider digital games for learning is that they allow for a wide range of ways to engage learners. Interaction has two important aspects, first is about relation between human and computer and the second is about the relation between human and human. (Prensky, 2001) Games imply the temporary acceptance of another type of reality so human and computer relation is different than human to real world relation. In games human-computer relation is provided by sound effects, dynamic graphics, and moreover in immersive games other sensory tools as 3D visualization, 3D sound, motion tracking and haptics are used to improve learning ability of students by grabbing their attention. Secondly, gamers can also prefer other human competitors and critique each other work. Like the internet, computer games are bringing people into closer social interaction in immersive or non immersive environments. The goal of integrating with interaction is to enhance cognitive engagement of the learner with the learning mechanic. Educational games that do not accomplish cognitive engagement are not able to be efficient in supporting the learner to achieve the specified task. (Plass, Homer, & Kinzer, 2015)

2.6.6. Representation

Representation can be named as essence of games. (Prensky, 2001) It contextualizes, narrates the game and indicates that game is about a subject, for example, chess is about conflict, Tetris is about building and recognizing patterns. Representation includes the element of fantasy which according to Malone and Lepper (1987) allows analogies and metaphors for real world processes that allow the user to experience phenomena from varied perspectives. In addition to that, fantasies offer people to interact in situations that are not part of real-world experience yet they are insulated from real consequences, namely a "world with no consequences". For example, students can learn physics by piloting a spaceship and entering earth's orbit, however, without fantasy and appropriate representation which gamifies this work, it can be left as simulation. Considering that, Rieber (1996) noted that because representation and fantasies are more closely linked to the learning content, if the fantasy is interesting enough, the content also becomes interesting. Furthermore, representation can be utilized to create motivate players. These features including extra-terrestrial structures, such as stars, points, leader boards, badges and trophies can create a high situational interest as well as game mechanics and activities that learners enjoy or find interesting. (Plass et al., 2015) Therefore, representation and fantasies are effective motivational tools when they internalized within the games.

2.7. Simulation and Education

Simulations narrow the focus of serious gaming by imitating and recreating an alternative reality within a controlled environment.(Ahmed & Sutton, 2017) They have held the promise of creating productive and engaging educational environments in science, technology, engineering and mathematics (STEM) domains. (Slavin, Lake, Hanley, & Thurston, 2014) Simulated educational games are experiential exercises that transport learners to another digital world. There, participants are able to apply their knowledge, skills and strategies in the execution of their assigned tasks. (Gredler, 2004)

Simulations provide many advantages not found in exercises with static problems. First, they bridge the gap between the student and the real-world in case of experience with complex and evolving problems. Second, they can reveal learner's misconceptions about the content. Third, they can provide information about students' problem solving approach.(Peterson, 2000) In this part, these positive outcomes will be explained by giving examples from the literature related to links between simulations and educational virtual reality applications.

For years virtual reality simulations are used in medical, aviation, military, sport industries and operative performances. One of the most simulation-education based area is medical surgery simulations. In modern healthcare sector, medical simulators are continuously being integrated into educational services offered to medical students, doctors and nurses. For example, patient-specific VR simulation has been possible by the evolution in the domains of virtual reality simulation and advancements in medical image processing. (Willaert, Aggarwal, Herzeele, Cheshire, & Vermassen, 2012) By the combination of MRI data and high-fidelity 3D mesh creation technology patient's virtual structures related to surgery are digitally formed and allows surgeon to manipulate the structure in a VR environment. The aviation industry is a significant example of an industry where simulation has major part in pilot training, performed in highly complex flight simulators which allow full conversion training of pilots with no real-time training in the actual aircraft. These simulators also are used for the design and engineering aircrafts as they allow accurate analyze and testing of prototypes in simulations. (Allerton, 2009) In addition to that simulation has been of considerable success in missions for fighter pilots such as a visual database of the combat field based on satellite data is generated within the flight simulator.

The basis of a simulation is a dynamic set of relationships among several variables that reflect authentic causal or relational processes. These relations can be emerged from physical or social reality and has to be designed as real as possible to create real-life experience in simulators. Therefore, lots of as real as possible features has to be added into simulations. For example when designing a military flight simulator; cone of angle, gravitational simulation to have realistic movement of planes, sound of the jets and the environment, real-life like artificial intelligence of other enemy planes and target system has to be primarily considered.

Simulations are also used in architectural education and profession regarding building performance, 3D modelling, construction process as a visualization tool for clients or construction site engineers. Although there are several industries including architecture utilizes interactive simulations in their education and professional life, there is no interactive simulation-based structure education method designed for architecture students or architects are found in the literature review. Yet, by considering the positive effects on other prime industries, the potentials of interactive simulations should be researched regarding that subject.

CHAPTER 3

METHOD OF INQUIRY: STRUCTUREPUZZLEVR

3.1. Structure Puzzle

As stated, the main purpose of this study is to make contribution to the literature by designing and understanding outcomes of a new DGBL environment by integrating IVLE and structural education. The name of the DGBL environment has been chosen as *“Structure Puzzle”* (SP), as it was believed that one of the most appropriate name for the game in terms of its working principle.

To have more comprehensible analyze of cause and effect relation the subject needed to be narrowed, thus long-span bridge structure typology has been chosen to apply. When bridges are examined, it can be seen that structure wise, there are not many types of long-span bridge elements according to case studies. Namely, long-span bridge typology can be clustered as main structural categories such as beam, arch, cable-stayed, suspension bridges. (W.-F. Chen & Duan, 2014) Therefore, comparing learning outcomes of students at the end of the sessions would be clearer and more revealing. Another reason of selecting bridge design as a case, since form of a bridge is directly related to its functional parts, the student's actions will be understood more clearly, and when the student's design is evaluated, an issue that is difficult to understand such as aesthetics will become more negligible. In addition to that, various topological relation between structural components in a bridge structure allows students to be more creative.

In other words, SP aims to understands the potentials and the role of IVLE related to its methodological integration as a learning medium for learning how to design and develop an insight about basic notion related to long-span bridge structures in the frame of digital game based learning theory.

3.2. Setting and Elements of Structure Puzzle

As stated before, Perkins (1991) indicates that every learning environment are composed of five key components including traditional classrooms. These are respectively information banks, symbol pads, phenomenaria, construction kits and task managers. Merging and reinterpreting these main elements with the features of IVLEs will be helpful and create more systematic definition of "immersive virtual learning environment" for structural education.

Information Banks are sources of information which includes textbooks, teachers, encyclopedias, videos, search engines, open source web libraries. Moreover, beside using all of these information repositories VR applications are also able to utilize open source digital model libraries, being able to share the same virtual library with people and giving feedback to each other by the help of various application in game engines.

Symbol Pads are surfaces for building and controlling symbols such as notebooks, computers, drawing programs and database programs which supports students' short-term memory. In this case, virtual environments designed in game engines permits learner to change the environment flexibly are used as an intermediary medium between user and the learning objective as a Symbol Pad. (Duffy & Jonassen, 1992)

Phenomenaria is a space where learner can go exploring and test their hypothesis. A part of every learning environment has to be reserved for phenomenaria. Examples include laboratory equipment, computational simulators and virtual worlds. When considering an immersive virtual environment, phenomenaria can be a learning by trying space situated in that virtual environment, which allows students to experiment various hypothesis side by side. Namely, a virtual space in a virtual space.(Duffy & Jonassen, 1992)

Construction Kits, allow learner to build entities from prefabricated parts such as Lego and Tinkertoy. In a digitalized world these prefabricated parts can be in various types, geometries and materials. These digitalized construction kits can be produced easier and faster than the real world. Furthermore, by the help of real-world imitator physics in game engines it gives IVLE designer more freedom in terms of budget, time and possibility of montaging these parts together. As the number of construction kits increases students will be confronted with as much as possible cases and get experienced more.

Finally, *Task Managers* are elements of the environment which guide, sometimes support and gives feedback to the students while finishing the task. Teachers are the evident example of task managers, also textbooks and computational programs can be in this category. In an IVLE, task managers can be pop-up windows which indicates negative or positive statements, moreover, various geometry and colors of 3D, 2D signs, animations can be used to navigate the students to the positive results.

Moreover, other tools being developed emphasize the use of communications or telecollaboration. This thrust is based on Vygotsky's theory of social constructivism, where students construct knowledge based on interactions with others.

3.3. Method of Inquiry

Gamificated IVR based simulation can be employed to enhance inexperienced architecture students' knowledge about basic concepts of statics and process of constructing long-span bridges. Moreover, after the implementation of the game, an inquiry method was created to understand how the game contributed to the education of the students and also to improve the game further as a feedback mechanism.

3.3.1. Research Questions

Under the light of the given hypothesis, the study interrogates these research questions:

- How can such IVR game be integrated into structural design education in architecture faculties?
- How beneficial would be an IVR game for creating a base for basic notions of structure design in terms of internalized by the students in case of long-span

bridge structure? (such as tension-compression, force equivalency, center of gravity)?

- Which educational theories or methods can be utilized while composing a conceptual base of designing long-span structures for students?
- How can outcomes of this structural IVR game be evaluated?

3.3.2. Objective Outcomes

- Proving that IVR based education can be more educative and joyful than traditional methods of teaching in some specific cases,
- Getting more familiar with the constructions and structural behaviors of beam, arch, cable-stayed and suspension bridges by experiencing them in first-person look,
- Having an overall intuition on how long span structures are standing and familiarized by their construction process
- Understanding notion of scale and proportion better by having an overall intuition on dimensions of structural elements (such as structural cables, joints) and bridge spans better,
- Developing different prototypes of long-span structures after a short time of IVR based education.

3.3.3. Participants

The experiment is conducted via voluntarily participation of second year architecture students from Middle East Technical University, Ankara, Turkey. The reasons behind choosing second year students are, first of all they can be named as novice ones while designing long-span structures. On the other hand, since they know basics of sketching, 3D drawing and technical drawing; in the first and the last session of the experiment they are able to show their design decisions on paper and open to develop different solutions to the given problems in the form of drawings and texts. Besides these, 1 fourth year architecture student and 1 graduate student with 2 years of architecture office experience are participated. In total, solutions of 14 participants have took part in this thesis.

3.3.4. Control Experiment and Control Group

Structure Puzzle departed into two parts, one is StructurePuzzleVR which is the structure game in virtual reality and the other is StructurePuzzleNotes that is written version of SPVR for the control group. In total 12 second year architecture students participate in the experiment, while 7 students participate in SPVR, other 5 participate in SPNotes.

3.4. Analysis Method: Bloom's Taxonomy and the SOLO Taxonomy

This thesis aims to propose a VLE as a tool to be used in architectural and structural education. However, without having the proper educational assessment method; the impact of the StructurePuzzle on the participants cannot be fully comprehended. Therefore, in order to select or hybridize an optimal method, the nature of the given task should be understood firstly.

There are many ways to assess outcomes of the experiential activities such as StructurePuzzle. These methods are tied to reflection, helping learners to focus their learning while also producing a product for the assessment purposes. Two of the most widespread and influential techniques are the Bloom's Taxonomy and the SOLO Taxonomy.

Bloom's Taxonomy specifically designed to provide teachers with a means of ordering items in terms of hierarchical level of quality. The method consists of six levels of response from basic to complex respectively; knowledge, comprehension, application, analysis, synthesis, and evaluation. (Bloom, 1984) Although Bloom's Taxonomy has been proved to be useful, it has some difficulties while assessing open-ended tasks as SP requires. First, the Bloom's Taxonomy is designed to guide the selection of items for a test rather than evaluation of the quality of a student's response to a particular item. (J Biggs & Collis, 1982) Therefore, teacher has to set strict predetermined goals on every six levels and expect students to reach these levels. However, since the teacher is not able to predict and classify all the answers before and after the assessment, it is creating a conflict while assessing an open-ended problem as the StructurePuzzle. Another drawback is related to a priori knowledge of students about basic structural behaviors and design of long-span bridges. Since the students has at least a little experience about structures before, they have already been starting from creation stage, in that case, the evaluation criteria of levels of the Bloom's Taxonomy are not suitable for the StructurePuzzle. Hence, SP requires better educational assessment method in terms of measuring variety and number of relations that is produced by the student between structural parts of the particular bridge for an open-ended task. On the contrary, SOLO taxonomy is more applicable for open-ended tasks, because it focuses on the structural complexity of any response given by the participants.

3.5. SOLO Taxonomy

The SOLO taxonomy is based on the study of outcomes of academic teaching. Biggs and Collins (1982) developed the SOLO (Structure of Observed Learning Outcomes) taxonomy as a systematic way of describing how a learner's performance develops in complexity when mastering tasks. The taxonomy derives from Piaget's theory of cognitive development and particularly the developmental stages in thinking. Several researchers who have applied SOLO due to it's comprehensiveness in application and its objective criteria provided for measuring students' learning outcomes. (Chan, Tsui, Chan, & Hong, 2002) Five different hierarchical levels according to the cognitive processes are composing SOLO. These levels are according to their increasing level of complexity; therefore, each partial level becomes a foundation on which further learning is built. The levels are respectively, prestructural (incompetence, nothing is known about the area), unistructural (one relevant aspect is known), multistructural (several relevant independent aspects are known), relational (aspects of knowledge are integrated into a structure) and extended abstract (knowledge is generalized to a new domain). (Hill, 1994) According to SOLO, these stages are not identical with, but derive from those developmental stage. Accordingly, in terms of evaluation, the levels focus on the structure of the responses that students give to particular learning tasks, rather than any concept of cognitive structure of the individual as it is in the Bloom's Taxonomy. (John Biggs & Tang, 2007) Assessment should measure the progress, not just the end-product. SOLO taxonomy moves evaluation of end-product to evaluation of problem solving and evaluation of how students build their solution against the problem. Therefore, SOLO can be more suitable for measuring level of education in open-ended tasks. The evaluation rubric and code phrases are explained below, under corresponding levels.

3.5.1. Prestructural

A prestructural solution composes if the participant does not understand what the question requires as an answer or avoids the question. Therefore, if the student cannot produce a solution by considering the major conditions indicated in the questions such as using specific types of structures as arches or pylons or placing foundations on infeasible spaces as waterways; the level of the student is determined as prestructural for that question. Moreover, if the student could not come up with any idea or find an irrelevant solution to the problem the educational level of the student is again determined as prestructural.

3.5.2. Unistructural

A unistructural solution provides a link between response and the given cue through one relevant aspect. If an answer is based on only one related aspect of the presented evidence, a limited and dogmatic conclusion occurs.

A solution of an arch bridge question can be named as unistructural response if,

- The student only designs arches and does not add any other minor supports as steel cables against vertical loads, bracings against lateral loads, or not considering vehicles passing through the bridge afterwards.

A solution of a cable-stayed and suspension bridge question can be named as unistructural response if,

- The student only designs pylons and does not add any other minor supports as steel cables contributing to overall structural stability,
- The participant does not design side spans.

3.5.3. Multistructural

A multistructural level occurs if the student considers several consistent aspects, but any inconsistencies or conflicts are ignored or discounted so that a firm conclusion is reached.

A solution of an arch bridge question can be named as multistructural response according to these several aspects.

- If an arch bridge composes of main parts as an arch beam and minor support elements, however the dimensioning and elaboration on the design of the arch beam is not feasible to construct a structurally stable bridge means that the student has knowledge of these general structural parts but does not have the detailed knowledge to elaborate on.

A solution of the cable-stayed and the suspension bridge question can be named as multistructural response by considering these reasons.

- If the bridge solution composes of structurally stable main parts as pylons and support elements, however dimensioning and section design of the pylons; placement and the angle of steel cables is in a condition to create an unstable bridge, which implies that the participant cannot relate the importance of these two major categories, therefore the educational level can be named as multistructural.

3.5.4. Relational

A relational response is more complex than a multistructural one. Rather than separating the parts of question, it provides multiple relevant aspects, information, data and relate them in a conceptual scheme.

A solution of an arch bridge question can be named as relational response according to these aspects.

- If the student successfully designs main parts as arch beams and minor support elements, moreover, if the dimensioning and elaboration on the design of the arch beam is feasible to construct a structurally stable bridge, which implies that the student has knowledge to relate all the aspects and used them in a conceptual scheme.

A solution of the cable-stayed and the suspension bridge question can be on relational level by considering these reasons.

If the bridge solution has successfully placed main parts of pylons and minor support elements, moreover if the design of the pylons and placement of the steel cables is in a condition to create an stable bridge, means that the student is able relate these two major categories, therefore the educational level can be named as relational.

3.5.5. Extended Abstract

An extended abstract response has what a relational response provides, but further conceptualise all the relevant aspects, information and their interrelations at a higher level of abstraction. It introduces an abstract principle, deductions and analogies which were not present as any sort of cue through the specific education; however the solution explores the compatibility with another and with the integrity of the whole response.

A level of a solution of a long-span bridge question can be defined as extended abstract response according to these aspects.

- If the student designs structurally stable bridge out of parts such as arches, pylons, decks or support elements, which is not shown in StructurePuzzleVR or SPNotes the educational level is extended abstract.
- If the student combine his priori knowledge and new knowledge acquired in StructurePuzzle education; so that create a new stable bridge parts the solution is an extended abstract solution.

3.6. Sessions

The experiment is composed of three sessions as Diagnostic Assessment I, Structure PuzzleVR and StructurePuzzleNotes, Diagnostic Assessment II respectively. Before the exercise nothing is given or announced to students. During or before the sessions, student is not informed whether there are other sessions coming or if the participant will be given questionnaire. There are 12 students departed into two groups 7 for SPVR experience and 5 for SPNotes as a control group. First session is more related to understand students' current knowledge about various types of long span structure design by asking case studies as a design problem on paper. The questions are related to arch, cable-stayed, suspension bridge design and lastly a large-span covering structure. The large-span covering question is out of particular context of long-span to understand if the participants are able to merge their knowledge in a new context. Second session is the educational part of the experiment; the groups are differentiated only in that phase; while first group is trained in SPVR the other group is taken into SPNotes application. In the last and the third session, both groups are asked to design bridges as it is in the first session on paper. When the experiment is finished the developments are analyzed between by comparing the answer sheets at the end of the first and the third sessions. Below, there is a graph narrating the process of the experiment.

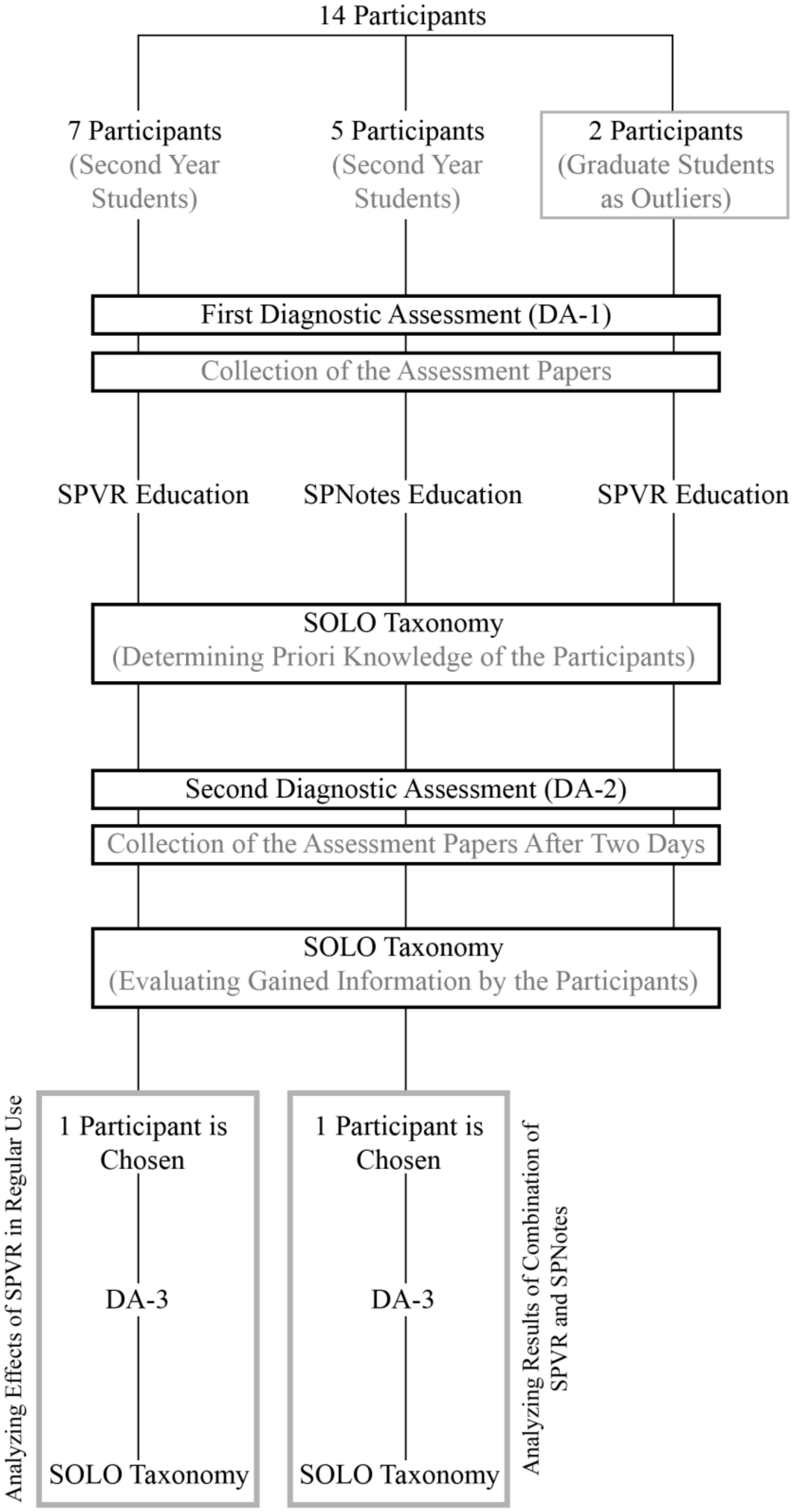

Figure 3.1. Experiment Process

3.6.1. Determination of Parameters for Analyzing the Results

Bridge design is a complex engineering problem. The design process includes basic parameters of a bridge which are bridge systems, materials, dimensions, foundations, aesthetics, local landscape and environment. Bridge design consists of two phases, first is preliminary and second is final design. While the most important is preliminary design phase which is about selecting and refining a bridge scheme; final design is more about calculations. Structure Puzzle aims to elaborate on preliminary phase. In order to avoid major problems in final design, a well-detailed and designed preliminary bridge scheme is needed. (Troitsky, 2000)

The processes and end-products can be investigated under several categories including analysis of basic parameters of a bridge, however after the experiment these can be varied or changed:

- Measurement, simply asking specific measurement values applied in virtual world and in diagnostic assessments, such as span structure, number of spans, uniformity or unequal spans, height, thickness of structural elements.
- Choice of material. if the student can relate the material and dimensions,
- Flow of forces, whether the students are able to show flow of forces as dissipation or transference.
- Tension-compression state, observing student ability to understand tension-compression, usage of cables and concrete elements together,
- Design of pylons, design of pylons are significantly important while designing a bridge,
- Design of foundations, (W. F. Chen & Duan, 2014)

Similarly, these are the base parameters that the IVLE game which is hypothesized by this thesis. Moreover, these basic concepts are also determining the criterion to analyze participants' long-span bridge design solution afterwards.

3.6.2. Session 1: Diagnostic Assessment-I (DA1) and Collection of the Data

First session is more about understanding students' knowledge about designing of long-span bridge structures. Couple of questions related with construction of beam, arch, cable-stayed, suspension and long-span covering structure, are asked to students on paper, which students are able to reflect their own current knowledge as sketches and texts on paper. During the assessments, students are required to take notes and show their process while reaching the end product. This information will be used for collection and comparison of the data in order to understand improvements on their designs.

The questions contextualizes different scenarios about constructing long-span bridges. For example, the first question gives axonometric and orthogonal views of 15 meters elevated 70 meters span horizontal bridge plate. The question is to stabilize the plate by using of arch or arches. There are couple of restrictions while designing the bridges such as unfeasible rock formation or water ways which participant cannot add any foundations on them. While answering or designing a solution for this, students are also expected to give dimensions and materials of the structural elements. Moreover, they are required to provide flow of forces, whether an assembly is under tension or compression.

The sketches are drawn on plan, section and axonometric views that are placed on A3 size sheet. The question sheet is prepared to have a minimum effect on student's decision-making process and to understand process of the student while designing the bridge. It is expected that by giving different views to draw on, students will be able to think in more dimensions about all the assemblies of their bridges.

While elaborating on these, in order to collect data and compare them afterwards, through the diagnostic assessment students are wanted to present:

- A brief paragraph on what has been learnt,
- Short answer questions of 'why' or 'explain' the participant took that particular action,

- Self-evaluation of a task performed as an option,
- Recommendation for improvement of some practice,
- A checklist or grader about objectives. (Moon, 2004)

To establish a better comparison and analysis scheme afterwards, students are only admitted use particular structural elements, such as arch or pylons, for each particular question. Moreover, in some cases, there are obstacles or restricted areas that forbids to place structural elements integrated into scenes, in order to open a space for students to reflect their creativity upon the sheet. Students have also limited time as 50 minutes to finish the test. In the end of the session, the question and answer papers are collected by the author.

This session is important for two reasons, first is for comparing before and after StructurePuzzleVR and StructurePuzzleNotes education, and the second is to understand priori knowledge level of the students about long-span structure design.

3.6.3. Session 2: StructurePuzzleVR and StructurePuzzleNotes

Session II is done just after the Session I on the same day. Second session is also sub-branched into two sessions. In the first sub session, 7 students are having 45 minutes long, interactive long span structure education by building bridges in a VR based application named StructurePuzzleVR (SPVR). The second group as a control group composed of 5 participants is having a 45 minutes education of long span structure on the paper that is StructurePuzzleNotes (SPNotes).

3.6.4. Session 2A: Elements of the StructurePuzzleVR

At that point, the VR application has to be explained to clarify several points. The name of the application given by the author is “Structure Puzzle” (SP). The application is designed in Unity 3D game engine software by the author and can be experienced by using Oculus Rift. Structure Puzzle is composed of different scenes as it was in the question paper for the first session. The application is sort of a structure simulator which allows user to build a long-span bridge by grabbing, snapping and dropping structural elements such as columns, beams, arches and structural cables to specified places. There are couple of scenes which problematizes from basic to more complex structural questions. By giving constant feedback and showing the direction of structural loads and indicating whether the elements are in compression or tension, it aids the students to develop these concepts. As it was in the first session, there are also restricted areas to place structural members, in order to develop participant's creativity by problematizing the question one level further. The first three scenes try to teach respectively basics of arch, cable-stayed and suspension bridges.

For example, for the first scene of building arch bridge, firstly, students are integrating a human size model of an arch bridge on which they are able to see how arch bridges transfer loads to the ground or deflected by applied force by the students. Secondly, the participant tries to construct several types of 1:1 scale bridge out of arches and if necessary, cables. For the whole scenes of arch, cable-stayed or suspension bridges, while in the first part fundamentals of static related schemes are narrated, in the second part students are expected to understand proportions and dimensions of the bridge.

Scene 1: Most Stable Shape

Rules (Constraints): Student is required to add the black boxes into gravity engines one by one, through that he has to guess which structure is more stable than the others under loading.

Goals and Objectives: Goal is demolishing the shapes.

Outcomes: The desired outcome is, students will see if force flows through the body of a structure evenly then that shape is more stable than the others. The ability to think and indicate force as a living creature instead of arrows and lines. Understanding triangle is more stable shape against loading, after that arch and lastly frame is more stable against vertical loading. This could be helpful while designing pylons in the second diagnostic assessment.

Feedback:

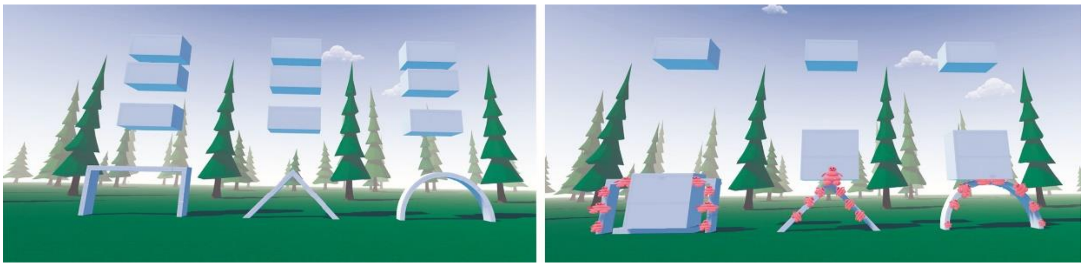

Figure 3.2. Shapes under load testing

"This is a loading test. We will see which geometry is more stable under loading. Do not forget that one of the essences of the structure is to transmit the forces through the earth on shortest path on its body. It has to be smooth and flowy. All the parts are mainly under compression, you can see Compreys. However, the frame structure demolished first. Because the load could not direct to earth as smooth as it is in triangle or arch. So, if you apply load on top of it, not all the parts of frame experience the same force magnitude. Therefore, there are overloading of load is taken by two sides on which the square is standing. The applied force on top of triangle is distributed all over the sides is equal. This means that there is no overaccumulation of forces on any parts.

Figure 3.3. Shapes under load testing

All the forces are flowing/going through the earth without any interruption which creates rigid and stable structure. Arch is also as this. Since arch is a pure compression form it is useful in many building materials, including stone and unreinforced concrete, can resist compression, however arches are weak when tensile stress is applied to them."

Conflict and Challenge: This scene is based on comparison than challenge; comparing and seeing three main types of geometry and flow of forces on them under loading in one scene.

Interaction: Interaction will be just between user and the black boxes. The sound of cracking and falling in order to understand the behavior of structures better.

Scene 2: Buckling and Fraction

Rules (Constraints): Student has to guess the final formation of the structures before adding gravity boxed into their places.

Goals and Objectives: Finishing seven simulations of concrete and steel structures by locating black gravity boxes into their places.

Outcomes and Feedback: Student will recognize behaviors of concrete and steel column beam structure. Moreover, s/he will be familiar with the ratios of height, section thickness and main span of different materials.

Feedback: "In this scene, you will learn the general ratio between span dimensions and section thicknesses of reinforced concrete and steel columns in a frame structure.

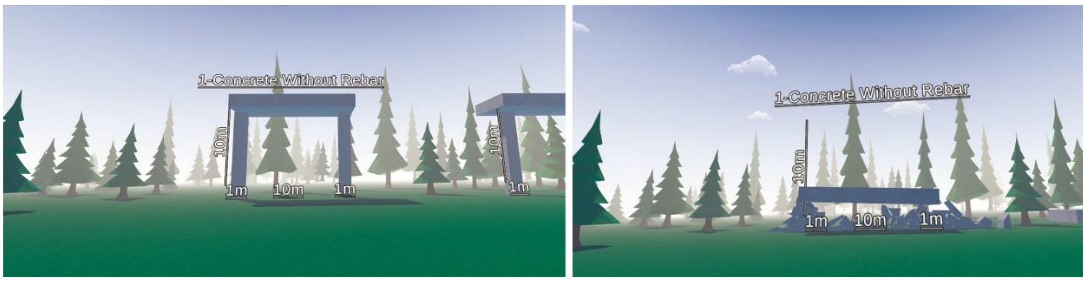

Figure 3.4. Behavior of concrete structure without steel under loading

Without rebars (steel bars) in concrete, it is just dust and ashes under loading. It stays only under compression and it could be devastated as this. Concrete is very strong in compression, but not strong in tension. Therefore, we add reinforcing steel for tensioning it a little against loading. This strengthens the concrete in tension and in shear. The ratio between section thickness of the reinforced concrete columns and span is 1m/10m=1/10.

Figure 3.5. Buckling in steel structure

Generally, this would be at least 1/20 in steel structures. So, it is stable under loading."

Conflict and Challenge: Challenge is to have true estimation of the structures under loading before adding the gravity to the scene.

Interaction: Interaction is only between black boxes and the participant. The sound of concrete cracking and bending steel in order to understand the behavior of materials better.

Scene 3: Catenary Arch-Shapened by the Gravity

Rules (Constraints): Rule is to snap and drop the pinned red cubes into different SnapDropZones (SDZ) installed on the wood plank.

Goals and Objectives: Objective is to place red pin cubes into different places.

Outcomes: The student will sense gravitational force as a shaper instead of a stand-still void. Student will see that this method is used in hanging bridges. While designing suspension bridge or arch bridge in DA-2 he can think of proportion of arch or hanging cables according to that. Seeing and getting familiar with ancient and modern examples will perceive the student about the durability and stability of an arch shape.

Feedback:

Figure 3.6. Hanging chain and finding optimum catenary arch ratio

“Catenary arch shape is created by pulling two sides of chain and releasing them. So, the whole structure is shapened by gravity and if a shape is shapened by gravity if you turn it upside down it can also work against gravity as well. What makes the catenary arch important is its ability to withstand weight. For an arch of uniform density and thickness, supporting only its own weight, every part of catenary is in perfect equilibrium that makes the catenary is the ideal curve. Catenary arch structure model of Sagrada Familia, Gaudi. After that he turned it upside down and it was the structure of the basilica.”

Conflict and Challenge: The scene is more about comparing different catenary arch curves.

Interaction: Interaction is only with red chained cubes and the student. The sound of chain application in order to memorize the key principle of composing catenary arch.

Scene 4: Aqueduct- Flow of Forces

Rules (Constraints): Student is only able to snap and drop arches in different places on top of the default given one storey arch. Second storey arches have to be lighter than the first storey and let people and animals to freely pass on second storey. New arches can only be placed two different positions, first is equally aligned with the base storey arches and the second is on top of the keystones of base arches.

Goals and Objectives: Goal is to add second storey and to construct the most stable viaduct as a whole.

Outcomes: Student will be familiar with more complex flow of forces and visualize compression behavior of cut-stone material. Moreover, participant will be able to relate weight, functionality and economy, so that s/he can use this information in DA-2 while designing an arch bridge or in the design of pylons by reducing their section thicknesses through their pitch point.

Feedback:

Figure 3.7. Double storey arche

“In the first setting there is no gravity yet. Do you think that it would be stable after the gravity added? In the second setting there is no gravity yet. Do you think that it would be stable (to which degree) after the gravity added? Think force as a glass of water flowing into your body. Try to stream it from your head through your body to your feet and to the earth. If the load stucks and accumulates on your belly or your kidney it could give you pain. So, give a way water to flow to reach the earth on your structure.

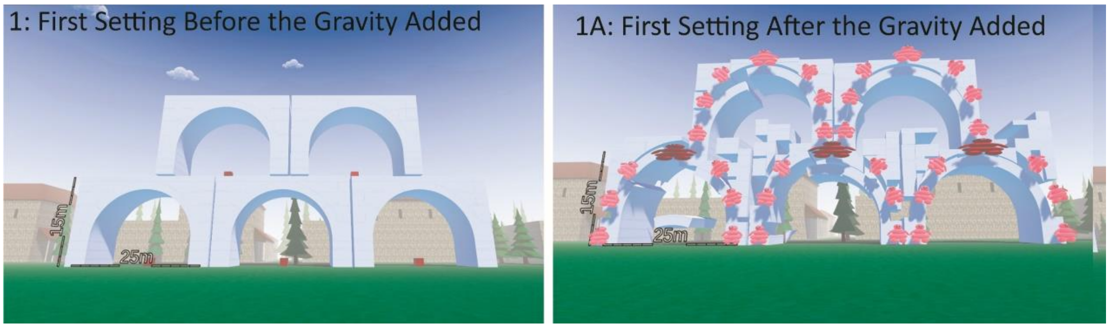

Figure 3.8. Double storey arches showing flow of forces

Do you see big dark red Compreys accumulated on the head of first storey arches? Since they cannot be able to flow more directly to the earth the structure is not that much stable and destructed more. Do you see big dark red Compreys accumulated on the head of first storey arches? Since they are more able to flow more directly to the earth through the leg of the arches on the first storey, the structure is more stable"

Conflict and Challenge: Student will be challenged by finding the most stable shape.

Interaction: The interaction will be between student, arches and SDZs. The sound of brick and stone cracking in order to understand the behavior of masonry better.

Scene 5: Deck Arch Bridge

Rules (Constraints): Rule is to place various types of solid, framed concrete and steel deck arch bridges by placing their foundations, arches, spandrel beams and anchors.

Goals and Objectives: Objective is to understand which bridge is more stable than the others.

Outcomes: Student is expected to recognize deck arch bridge. Moreover, s/he will be able to perceive parts and flow of forces in a modern arch bridge by constructing it from foundation to spandrel beams. Compared to scene four, which uses stone arch bridge, student will understand behavior of concrete and steel.

Feedback:

Figure 3.9. Types of arches and a construction crane

“Arch bridges are one of the oldest types of bridges and have great natural strength. As you saw in other scenes, arches are used in long span bridge typology and other long span structures. There are different types of arch bridges. One of them is deck arch bridge which comprises an arch where the deck (road that is used by car, people...) is completely above the arch. Typically, modern arch bridges span between 60-250 meters of span. Span is the distance between two intermediate supports for a structure. The typically used ratio of rise-to-span for steel arch bridges is in the range of 1:5 to 1:6. The area between the arch and the deck is known as the spandrel. Do you see Comprey? Or any Tensey? The concrete arch is in compression. The framed arch stays stable as it was in solid concrete arch. Which one of the arches are used more concrete? However, both are as stable as each other, right? So, which one of them do you prefer to use?

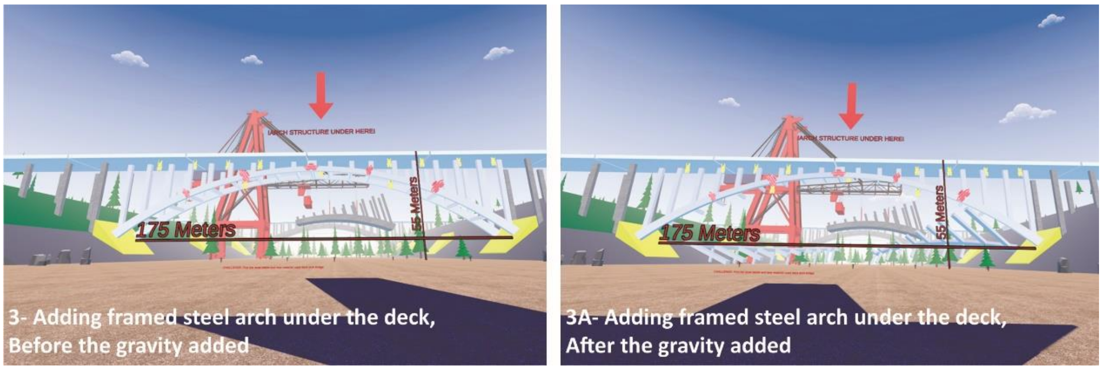

Figure 3.10. Framed steel arch and its devastation under vertical loading

However, after the gravity added the framed steel arch could not stand well. What could be the reason for this? If you think steel as marshmallow and the concrete as a cookie, marshmallow can be bent or compressed easily but can be more open for displacement against impacts. However, a cookie can only be compressed and hard to be displaced by the impact. One of the reasons is that, since steel is softer material than the concrete it could easily bend against impact, especially against compression. To cope with that, the perpendicular frames has to be strengthened by other steel supports. Which as you know by triangular trusses or so."

Conflict and Challenge: Challenge is to understand why certain types of bridges are not stable or stable.

Interaction: Between boxed and the student. The sound of concrete and steel application in order to understand the behavior of different materials better.

Scene 6: Through Arch Bridge

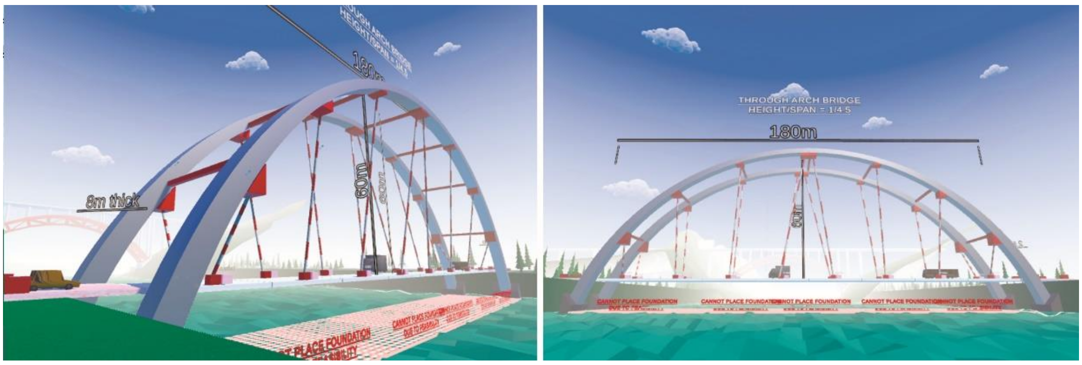

Figure 3.11. Through arch bridge integrated with steel cables

Rules (Constraints): Student should try different ratios of through arch bridges and choose height and span ratio is applicable and more stable. Moreover, s/he has to pay attention to truck and car size which will use the bridge later and has to consider strong prevailing wind coming from the side.

Goals and Objectives: The objective is to select the most stable arch bridge formation.

Outcomes: Student will be able to recognize concept of through arch bridge,

By experiencing it and walking on it in a real-world example student will be able to understand dimensions better.

Being able to understand the balance between cable tension and solid compression,

Considering height/span ratio, flow of forces on arch, cable and deck by using them together,

Being able to visualize wind as a structural design parameter,

Understanding importance of symmetry even in asymmetric examples,

Feedback: “What type of bridge are you able to design for the situation on the left picture? The span is 180 meters and the height difference between river surface and the topography is 7 meters. Try to design a deck bridge here.

Figure 3.12. Deck arch bridge and through arch bridge construction

Sometimes engineers are not allowed to design a deck arch bridge due to ratio between span length and height of an arch. The typically used ratio of rise-to-span for steel arch bridges is in the range of 1:5 to 1:6. However in the first example, this ratio of deck arches even if with 3 different arches are 1/8. And if it is wanted to be done with one arch the ratio is 180/7.5 = 24 So that this situation requires to design a through arch bridge.

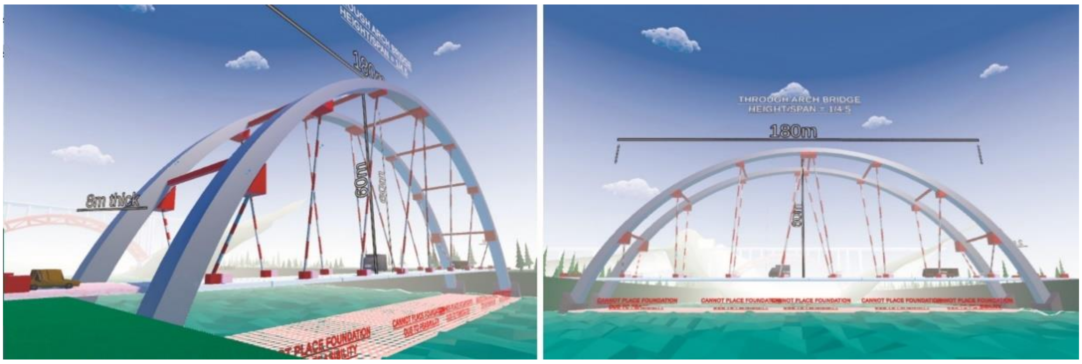

Figure 3.13. Through arch bridge integrated with steel cables

This requires a structure that can both support the deck from the arch by tension rods, chains or cables and allow a gap in the arch, so the deck can pass through it. Moreover, as it was in the trussed deck bridge example, there has to be several supports between two arches against wind loads. The formation of arches does not have to be parallel to the deck, there are several types of through arch bridges."

Challenge: The challenge is to relate the stability and the most appropriate ratio of a through arch bridge formation.

Interactivity: Interactivity is between student, boxes and wind turbine. The sound of concrete, steel and steel cable application in order to understand the behavior of different materials better.

Cable-Stayed Bridge Scenes

Scene 7: Pylon Types

Rules (Constraints): Student is required to first select the most stable pylon type against the wind and place a white box into wind turbine engine so that turbine power is applied on the structures as a lateral load.

Goals and Objectives: The most stable pylon according to student has to stand still as last.

Outcomes: Recognizing various shapes of pylons, Understanding relation between weight, gravitational center,

Recognizing “I, A, H, Y, inverted Y” and rectangular types of pylons,

Feedback:

Figure 3.14. Various pylon types against wind turbine

“There are not only arch bridges is for long-span bridges to construct. Cable stayed and suspension bridges are other main typologies of long-span bridges. Different than the arch bridges these requires pylons and steel cables (large columns so to call). In this scene, we will understand the behaviors of various types of columns against vertical and lateral loading. Pylon types are generally categorized under I, H, Y, A, and inverted Y. Here you can see the red spheres on pylons which are indicating their weight and gravitational centers. Which one of the pylons would you think that be more stable against wind or vertical loading?

Figure 3.15. Wind turbines and behavior of pylons against the wind

Normally, as the gravitational center is close to ground, we would expect that it would be to more stable against the external forces. However, it is not the all the case. For example, for the second Y type pylon in the image; the weight and the gravitational center seems enough to be stable against the wind.

Challenge: The challenge is to think about the last stable among 13 different types of pylon.

Interactivity: The interactivity is between student, white cube and the wind tunnel. The sound of wind is added in order to be identified wind as a major structural force by the participant.

Scene 8: Cable Arrangement; Mono, Harp, Fan, Star

Rules (Constraints): Student is required to add foundation, pylon, deck and different types of steel cable formation. After that student has to guess whether fan or harp type formation is more stable to hold the deck and then start the gravity simulation.

Goals and Objectives: Goal is to find the most stable cable arrangement and explaining the reason behind this.

Outcomes: Recognizing cable-stayed bridge,

By experiencing it and walking on it in a real-world example student will be able to understand dimensions better,

Understanding construction phases of cable stayed bridge and through that understanding flow of forces,

Understanding why fan shape is more stable and powerful.

Feedback*:*

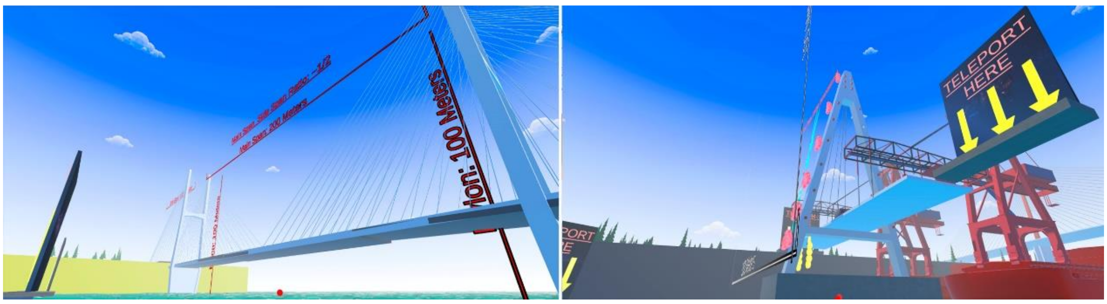

Figure 3.16. Different cable-stayed bridge types and construction method

“A cable-stayed bridge is a structural system with a continuous girder supported by inclined stay cables from the pylons. The cable-stayed bridge ranks first for a span range approximately from 150 to 600 m, which has spanning capacity longer than that of cantilever bridges, truss bridges, arch bridges, and box girder bridges, but shorter than that of suspension bridges. The ratio between main span/pylon height generally is 1/1. The steel cables are anchored to the pylons and deck, so that the cables are always in tension and pylons are in compression. Load is transferred from deck to cables to pylon and to the earth.

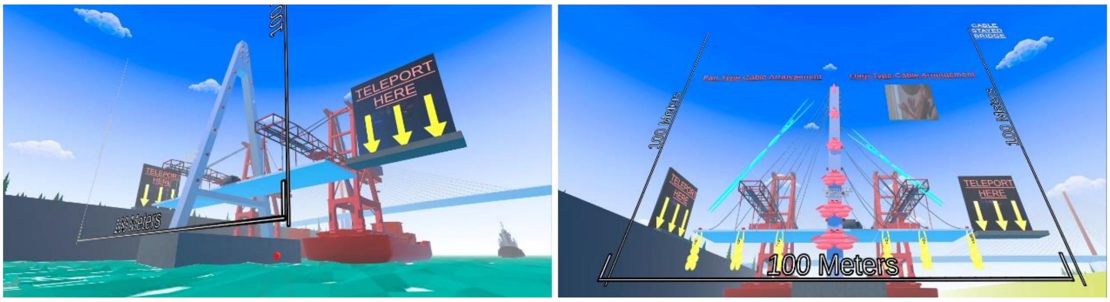

Figure 3.17. Different cable formations

In fan type, all the cables are attached to a nearly single point, in harp type all the cables are parallel to each other. Fan type is more load bearing because the force vectors of cables are doing more work against gravity because their y vector is more dominant than the harp type’s y vector. However, some designers prefer harp type because they believe that it looks more aesthetic.”

Challenge: Challenge is thinking about construction phase and guessing which cable arrangement is more stable.

Interactivity: Interactivity is between student foundation, pylon, cables and powering gravitational simulation. The sound of concrete, steel and steel cable application in order to understand the behavior of different materials better.

Scene 9: Single Spar Cable-Stayed Bridge

Rules (Constraints): Student has to place three types of pylon which are vertical, back-leaning and front leaning, after that link steel cables where he senses that it is needed.

Goals and Objectives: Goal is to build a stable single spar cable stayed bridge.

Outcomes: Student will be able to recognize and build a single spar cable stayed bridge,

Relating the force equilibrium between weight and angle of pylon with steel cables,

Getting more familiar dimensions of single spar bridge.

Feedback:

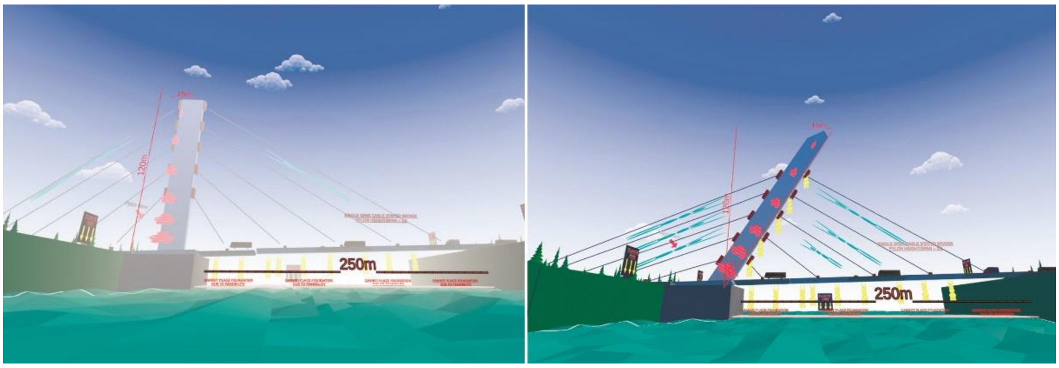

Figure 3.18. Vertical and front leaning single spar bridges under loading

"As its name states there is mono span for this type of bridges. Only one pylon holds all the deck by the help of anchored steel cables. Perpendicular pylon requires steel cables for both of its sides, since there is no balancing force if you have cables on just one-side it would collapse. In this example, the cables carrying deck are in tension and connecting to the pylon. While cables are dragging the pylon on one side the weight of the pylon balances the structure so that there is no cable needed for the other side.

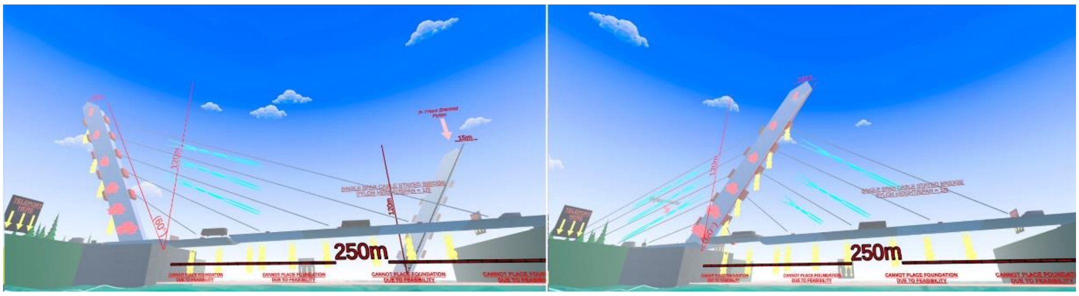

Figure 3.19. Back and front leaning single spar bridges under loading

Forward angled pylon requires steel cables for both of its sides, since there is no balancing force if you have cables on just one-side to carry the deck it would collapse. Therefore, other side also needs steel cables. Think of tension stress difference on the cables on both sides."

Challenge: Challenge is to find the optimum cable configuration for different angled pylons.

Interactivity: Interactivity is between student, cables and gravity simulation. The sound of concrete, steel and steel cable application in order to understand the behavior of different materials better.

Suspension Bridge Scenes

Scene 10: Ratio Between Main Span,Side Span and the Height of Pylons

Rules (Constraints): Student is required to power gravity simulation on four different ratios of suspension bridge prototypes. These ratios are related with height of pylons, main span and side span.

Goals and Objectives: Goal is to finish four of the simulations.

Outcomes: Student will recognize suspension bridge typology and its working principle.

By differentiating it from cable-stayed bridges s/he could understand that larger spans can only be passed by a bridge based on tensioning.

Student will understand the ratios between height of pylons, main span and side span are important principle in terms of stability in suspension bridges.

Feedback:

Figure 3.20. Structure simulations of different ratios of bridge components

“There is a generalized ratio between main span and side span of suspension bridges. The ratio between main span and side span be less than 0.5 to give the emphasis to the main span. Generally optimum ratio of side span/main span is 0.4-0.45 (Bennett, 2008). In this example the ratio is about 0.1. If the side span/main span ratio is too low as in this example, the pylons can be destructed by the uncontrollable force due to steel cables. However, if the span ratio is enough, the forces can flow from deck to main cable to pylons. In this example the ratio is about 0.4.

Figure 3.21. Structure simulations of different ratios of bridge components

The height of the pylon is also important. Usually ratio of pylon to total span is 1/9 or 1/10. Think if the height of the pylon is too high, what would happen? Here is the ratio of main/span to side span is about 0.5, however since the pylon is too high the angles of the steel cables also too steep.”

Challenge: Challenge is to pick the best ratio which composes the most stable suspension bridge.

Interactivity: Interaction is between student, steel cables and gravity simulation. The sound of steel cable in order to show the student the relation between suspension bridge and steel cables better.

Scene 11: Chavanon Bridge-Constructing a Suspension Bridge

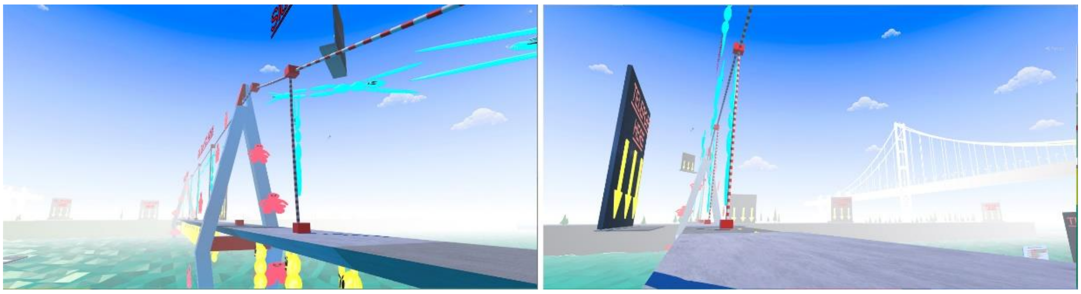

Figure 3.22. Simulation of a mono-cable suspension bridge

Rules (Constraints): Student has to add foundations, pylons, decks and cables linking them and complete the process by powering the gravity engine to release the bridge components.

Goals and Objectives: Student should understand relations between stable suspension bridge components.

Outcomes: By experiencing it and walking on it in a real-world example student will be able to understand dimensions and working principle of suspension bridge better.

Feedback*:*

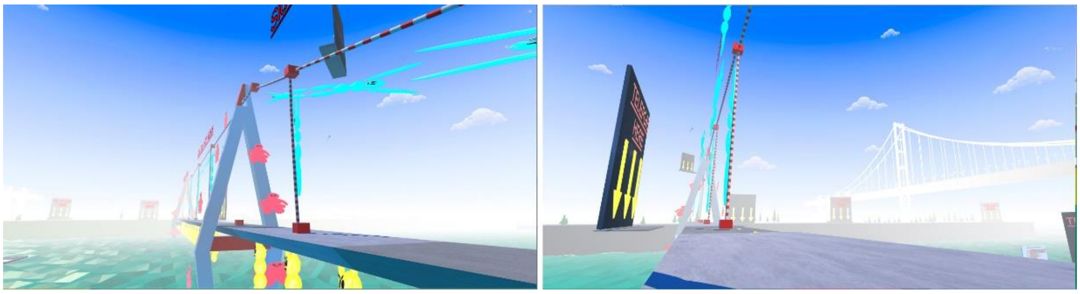

Figure 3.23. Simulation of a mono-cable suspension bridge

"Tower carries the main cables. Foundation and support anchors provide main cable to stay in tension. Suspension cables transfer load of the deck to main cable to tower to foundation and lastly to the earth.

Figure 3.24. Simulation of a mono-cable suspension bridge

Usually a ratio of pylon height to total span is 1/9-1/10. Think if the pylons are 20 meters what will happen?"

Challenge: The challenge is inferring relations between bridge parts.

Interactivity: Interactivity is between student, main cable, connection cables and foundation.

3.6.5. Session 2B: Elements of the StructurePuzzleNotes

The other group is given notes on papers as an education medium, namely StructurePuzzleNotes. The notes are the written form of what StructurePuzzleVR is. It is added into appendix of this thesis. Namely, it is composed of colorful diagrams, graphics, 3D and orthogonal drawings of scenes in SPVR and couple of solution for these structure questions. The main difference between the first and the second group is that, while the first group is performing an interactive and experiential learning, the second group is having relatively traditional education which is present in most schools.

During these sessions, participants are not informed anything about the third session. As the scenes are progressed, through the last scenes it lets students to use more variety types of structural elements so to force students to reflect more creativity and see as much as possible example.

Below the differences and similarities of SPVR and SPNotes are discussed in a graphic.

Table 3.1. *Differences and Similarities Between SPVR and SPNotes*

SPVR and SPNotes Comparison		
Features	**StructurePuzzleVR**	**StructurePuzzleNotes**
Haptics (Interaction)	-Grabbing, moving and seeing behaviours of pylons, steel cables, chains	(-)
Movement	-3D movement -Enabling teleport to save time while learning, sudden camera is integrated so that students are able to perceive the scenes through design process from wide ranges of perspectives.	(-)
Material	-Color, gloss, audio effects of steel, concrete and cables	-Color, gloss
Dimension	-Immersive Visualization -Fog -Pace of movement, standart walking speed	-Couple of axonometric and perspectival images from the scenes.
Physics (Effects of Vertical and Lateral Loads, Cautions Against Wind)	-Unity 3D Physics Engine to understand behaviours of various materials and structures. -Showing process of tensioning behaviour of the steel cables under loading, structures against wind load. -Stereo audio effects of the wind to show the participant the direction is important.	-Being able to show the images of the structures through vertial and lateral loading process.
Flow of Forces	-Continuous visualization of the relation between tension and compression forces	-Images showing tension and compression forces
Instructions	-Verbal explanations through SPVR	-Written explanations

3.6.6. Session 3: Diagnostic Assessment II (DA2) and Collection of Data

Third session starts after one week having a short educational exercise in the second session. The reason behind the one-week gap is to give a time to student to internalize the knowledge about what has been learnt. Third session can be named as slightly copy of first session. The design medium is again paper, however in order to understand if the participant is able to apply the learning from the second session; this time the questions are slightly different such as by changing the restricted places, form of the bridge plates, spans for the environment for some student. Besides some of the students are answering slightly different questions some of them are directed the same questions asked in the first sessions. So, there are other sub-control groups in VR and Notes groups. While designing bridges on the paper, students are also required to write couple of sentences indicating how and why they took that particular decision. After the session is finished, the papers are collected to compare them with the papers collected after the first session is finished.

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Classification and Analyzing the Data

After collecting all the diagnostic assessment sheets of 12 bachelor and 2 graduate students, an assessment rubric is designed by considering the criterion for evaluation of the works. The evaluation method considers individual improvements of the students among their solution sheets. Therefore, the rubric has been prepared in line with the educational levels of the SOLO Taxonomy and basic parameters for the evaluation of long-span structures indicated in the third chapter before. For each student, four question sheets are analyzed. There are common and particular analyze parameters for each different question, to illustrate, while parameters related to stability, material, dimensions and ratios are common in every analyze sheet, the ratios and types of megastructures differs according to every bridge question.

For arch, cable-stayed and suspension bridges, each of 30 diagnostic assessment papers are analyzed according to 11 different categories composed of participants' decisions related to determined parameters. Similarly, for the long-span covering structure question which is relatively more open-ended one, 30 diagnostic assessment papers are analyzed according to 8 different categories.

In total 120 diagnostic assessment papers are analyzed and 1230 individual decisions are issued. According to the analysis, the overall improvements of students are noted and their levels are indicated as prestructural, unistructural, multistructural, relational or extended abstract.

4.2. General Observations on Analysis

In this section, firstly general observations regarding the assessment results of undergraduate students; after that inferences on two graduate students are mentioned. Lastly, the performances of P-05 who have third diagnostic assessment in order to understand SPVR’s benefits the long-term use and the performances of P-12 in order to understand benefits of SPNotes and SPVR when used in combination is discussed specifically.

The general observations are done separately according the questions one by one by comparing the 7 undergraduate and 2 graduate participants which had been educated in SPVR; 5 undergraduate students in SPNotes.

Considering the arch bridge question, 10 of 12 students’ designs advance between two design sessions, while P-04 and P-05 who are taken into SPNotes display no advancement. While no participant advances beyond multistructural level in any group, according to results of DA-2; 3 extended abstract and 4 relational level performances can be seen within the SPVR group. Yet, only 1 relational and extended abstract advancement are observed out of 4 performances in SPNotes group. The experiment results show that SPVR is more capable of teaching behavior of arch bridge structures than the SPNotes.

Moreover, although both DA-1 results of graduate students are in slightly same levels of undergraduate ones, after having SPVR education they reached extended abstract level by designing more detailed structures than undergraduate participants.

Similar to that, performances of P-05 progressively reach more advanced levels from multistructural to extended abstract. Through the assessments the participant is able to elaborate more on the question, moreover s/he verbally indicates that s/he is able to internalize the knowledge better. Parallel to that, although the performances of P-12 is unistructural level for the first two diagnostic assessments, after having SPVR education s/he is able to reach extended abstract. The participant also verbally indicates that, the combination of SPNotes and SPVR is very beneficial in terms of internalizing the knowledge.

Table 4.1. *Results of Arch Bridge Question*

ARCH BRIDGE QUESTION				
Participant Number	**Media**	**DA-1**	**DA-2**	**DA-3**
1 (DA1-DA1)	**SPVR**	PRESTRUCTURAL	EXTENDED ABSTRACT	
2 (DA1-DA1)	**SPVR**	PRESTRUCTURAL	EXTENDED ABSTRACT	
3 (DA1-DA21	**SPVR**	MULTISTRUCTURAL	RELATIONAL	
5 (DA1-DA2-DA2)	**SPVR (2 Times)**	MULTISTRUCTURAL	RELATIONAL	EXTENDED ABSTRACT
7 (DA1-DA1)	**SPVR**	PRESTRUCTURAL	RELATIONAL	
8 (DA1-DA1)	**SPVR**	UNISTRUCTURAL	EXTENDED ABSTRACT	
9 (DA1-DA1)	**SPVR**	MULTISTRUCTURAL	RELATIONAL	
13 (DA1-DA2) (Graduate)	**SPVR**	MULTISTRUCTURAL	EXTENDED ABSTRACT	
14 (DA1-DA2) (Graduate)	**SPVR**	MULTISTRUCTURAL	EXTENDED ABSTRACT	
4 (DA1-DA2)	**SPNotes**	PRESTRUCTURAL	PRESTRUCTURAL	
6 (DA1-DA2)	**SPNotes**	PRESTRUCTURAL	UNISTRUCTURAL	
10 (DA1-DA2)	**SPNotes**	UNISTRUCTURAL	RELATIONAL	
11 (DA1-DA2)	**SPNotes**	MULTISTRUCTURAL	EXTENDED ABSTRACT	
12 (DA2-DA2-DA2)	**SPNotes and SPVR**	UNISTRUCTURAL	UNISTRUCTURAL	EXTENDED ABSTRACT

LEGEND				
PRESTRUCTURAL	UNISTRUCTURAL	MULTISTRUCTURAL	RELATIONAL	EXTENDED ABSTRACT

7 of 7 SPVR group performances are advances either as relational or extended abstract level in cable-stayed bridge question. However, there is 3 of 4 SPNotes group performances are only be able to reach multistructural level. Although the results of the all participants after DA-1 are similar to each other; this advancement shows that SPVR is more effective in teaching structural behavior of cable-stayed bridges. In addition to that, though the first result of both graduate students are in the same level as undergraduate students, after DA-2 one of them reached extended abstract and other reached relational level by designing more detailed cable-stayed bridge than undergraduates.

Although the performances of P-12 are only able to reach multistructural level for the first two diagnostic assessments, after having SPVR the participant's third arch bridge solution gets more complex and reaches relational level.

Table 4.2. *Results of Shorter Span Cable-Stayed, Suspension Bridge Question*

SHORTER-SPAN BRIDGE QUESTION				
Participant Number	**Media**	**DA-1**	**DA-2**	**DA-3**
1 (DA1-DA1)	**SPVR**	PRESTRUCTURAL	EXTENDED ABSTRACT	
2 (DA1-DA1)	**SPVR**	RELATIONAL	EXTENDED ABSTRACT	
3 (DA1-DA21	**SPVR**	MULTISTRUCTURAL	EXTENDED ABSTRACT	
5 (DA1-DA2-DA2)	**SPVR (2 Times)**	MULTISTRUCTURAL	RELATIONAL	RELATIONAL
7 (DA1-DA1)	**SPVR**	MULTISTRUCTURAL	EXTENDED ABSTRACT	
8 (DA1-DA1)	**SPVR**	MULTISTRUCTURAL	RELATIONAL	
9 (DA1-DA1)	**SPVR**	RELATIONAL	EXTENDED ABSTRACT	
13 (DA1-DA2) (Graduate)	**SPVR**	MULTISTRUCTURAL	RELATIONAL	
14 (DA1-DA2) (Graduate)	**SPVR**	MULTISTRUCTURAL	EXTENDED ABSTRACT	
4 (DA1-DA2)	**SPNotes**	MULTISTRUCTURAL	PRESTRUCTURAL	
6 (DA1-DA2)	**SPNotes**	RELATIONAL	MULTISTRUCTURAL	
10 (DA1-DA2)	**SPNotes**	UNISTRUCTURAL	MULTISTRUCTURAL	
11 (DA1-DA2)	**SPNotes**	MULTISTRUCTURAL	MULTISTRUCTURAL	
12 (DA2-DA2-DA2)	**SPNotes and SPVR**	MULTISTRUCTURAL	MULTISTRUCTURAL	RELATIONAL

LEGEND				
PRESTRUCTURAL	UNISTRUCTURAL	MULTISTRUCTURAL	RELATIONAL	EXTENDED ABSTRACT

The results of suspension bridge question are also similar to cable-stayed bridge question. Besides having 1 relational level performance and other similar performances near to prestructural and multistructural levels in each SPVR and SPNotes category regarding analysis on DA-1; after DA-2, degree of advancements between the two groups differ greatly. Namely, while 2 relational and 5 extended abstract performance SPVR group are observed, SPNotes group has 4 multistructural and 1 unistructural performances. Moreover, through the analysis even though it is not highly observed, some of the educational levels of some participants from SPNotes group are tend to decrease from DA-1 to DA-2. The fact that SPNotes is less stimulating than the SPVR can cause the student to become more confused, more careless or not to elaborate on answering the questions because of lack of attention and attraction of the application.

In addition to that, as it is in the arch bridge question although the first result of both graduate students are in multistructural and unistructural level similar to majority of undergraduate students, after DA-2 both of them reaches extended abstract level by designing more detailed long span suspension bridges.

Performances of P-05 gets better through s/he had SPVR progressively. Although she started as prestructural level, after having two SPVR education s/he is able to design more complex and detailed suspension bridge of extended abstract level. Although the performances of P-12 reaches multistructural level for the first two assessments, after taken into SPVR, the participant's last design gets more detailed and reaches relational level.

Table 4.3. *Results of Longer Span Suspension, Cable-Stayed Bridge Question*

LONGER SPAN BRIDGE QUESTION				
Participant Number	**Media**	**DA-1**	**DA-2**	**DA-3**
1 (DA1-DA1)	**SPVR**	PRESTRUCTURAL	EXTENDED ABSTRACT	
2 (DA1-DA1)	**SPVR**	RELATIONAL	EXTENDED ABSTRACT	
3 (DA1-DA21	**SPVR**	MULTISTRUCTURAL	EXTENDED ABSTRACT	
5 (DA1-DA2-DA2)	**SPVR (2 Times)**	PRESTRUCTURAL	RELATIONAL	EXTENDED ABSTRACT
7 (DA1-DA1)	**SPVR**	UNISTRUCTURAL	EXTENDED ABSTRACT	
8 (DA1-DA1)	**SPVR**	MULTISTRUCTURAL	RELATIONAL	
9 (DA1-DA1)	**SPVR**	MULTISTRUCTURAL	EXTENDED ABSTRACT	
13 (DA1-DA2)(Graduate)	**SPVR**	MULTISTRUCTURAL	EXTENDED ABSTRACT	
14 (DA1-DA2)(Graduate)	**SPVR**	UNISTRUCTURAL	EXTENDED ABSTRACT	
4 (DA1-DA2)	**SPNotes**	MULTISTRUCTURAL	MULTISTRUCTURAL	
6 (DA1-DA2)	**SPNotes**	UNISTRUCTURAL	UNISTRUCTURAL	
10 (DA1-DA2)	**SPNotes**	UNISTRUCTURAL	MULTISTRUCTURAL	
11 (DA1-DA2)	**SPNotes**	RELATIONAL	MULTISTRUCTURAL	
12 (DA2-DA2-DA2)	**SPNotes and SPVR**	MULTISTRUCTURAL	MULTISTRUCTURAL	RELATIONAL

LEGEND				
PRESTRUCTURAL	UNISTRUCTURAL	MULTISTRUCTURAL	RELATIONAL	EXTENDED ABSTRACT

According to the results, 5 of 7 SPVR and 4 of 5 SPNotes are relational level performances, the other three results are in multistructural and prestructural levels. However, according to results of DA-2, 3 relational level performances of SPNotes group are declined into multistructural levels while 4 relational level performances of SPVR advances into extended abstract level.

Along with that, despite graduate students results regarding long-span covering question are similar to undergraduate students; they are able to provide more detailed solutions.

After having two times SPVR education, P-05 is able to design more complex and detailed long-span covering bridge that reaches extended abstract level. In the end, she is able to integrate his/her design by the knowledge not even present in SPVR.

Table 4.4. *Results of Long-Span Covering Question*

LONG-SPAN COVERING QUESTION				
Participant Number	**Media**	**DA-1**	**DA-2**	**DA-3**
1 (DA1-DA1)	**SPVR**	RELATIONAL	MULTISTRUCTURAL	
2 (DA1-DA1)	**SPVR**	RELATIONAL	EXTENDED ABSTRACT	
3 (DA1-DA21	**SPVR**	RELATIONAL	RELATIONAL	
5 (DA1-DA2-DA2)	**SPVR (2 Times)**	PRESTRUCTURAL	MULTISTRUCTURAL	EXTENDED ABSTRACT
7 (DA1-DA1)	**SPVR**	MULTISTRUCTURAL	RELATIONAL	
8 (DA1-DA1)	**SPVR**	RELATIONAL	EXTENDED ABSTRACT	
9 (DA1-DA1)	**SPVR**	RELATIONAL	RELATIONAL	
13 (DA1-DA2)(Graduate)	**SPVR**	RELATIONAL	EXTENDED ABSTRACT	
14 (DA1-DA2)(Graduate)	**SPVR**	MULTISTRUCTURAL	EXTENDED ABSTRACT	
4 (DA1-DA2)	**SPNotes**	RELATIONAL	EXTENDED ABSTRACT	
6 (DA1-DA2)	**SPNotes**	UNISTRUCTURAL	UNISTRUCTURAL	
10 (DA1-DA2)	**SPNotes**	RELATIONAL	MULTISTRUCTURAL	
11 (DA1-DA2)	**SPNotes**	RELATIONAL	MULTISTRUCTURAL	
12 (DA2-DA2-DA2)	**SPNotes and SPVR**	RELATIONAL	MULTISTRUCTURAL	RELATIONAL

LEGEND				
PRESTRUCTURAL	UNISTRUCTURAL	MULTISTRUCTURAL	RELATIONAL	EXTENDED ABSTRACT

4.3. Examples of Evaluation and Comparison of the Responses

After collecting solution papers from the participants, the bridge proposals are examined according to base bridge parameters given before. The numerical, graphical, text-based explanations are considered while analyzing the solutions. Details of how bridge design solutions are evaluated and compared between diagnostic assessments according to SOLO Taxonomy are given below.

Participant 1– SPVR – Arch Bridge Question - (Prestructural to Extended Abstract)

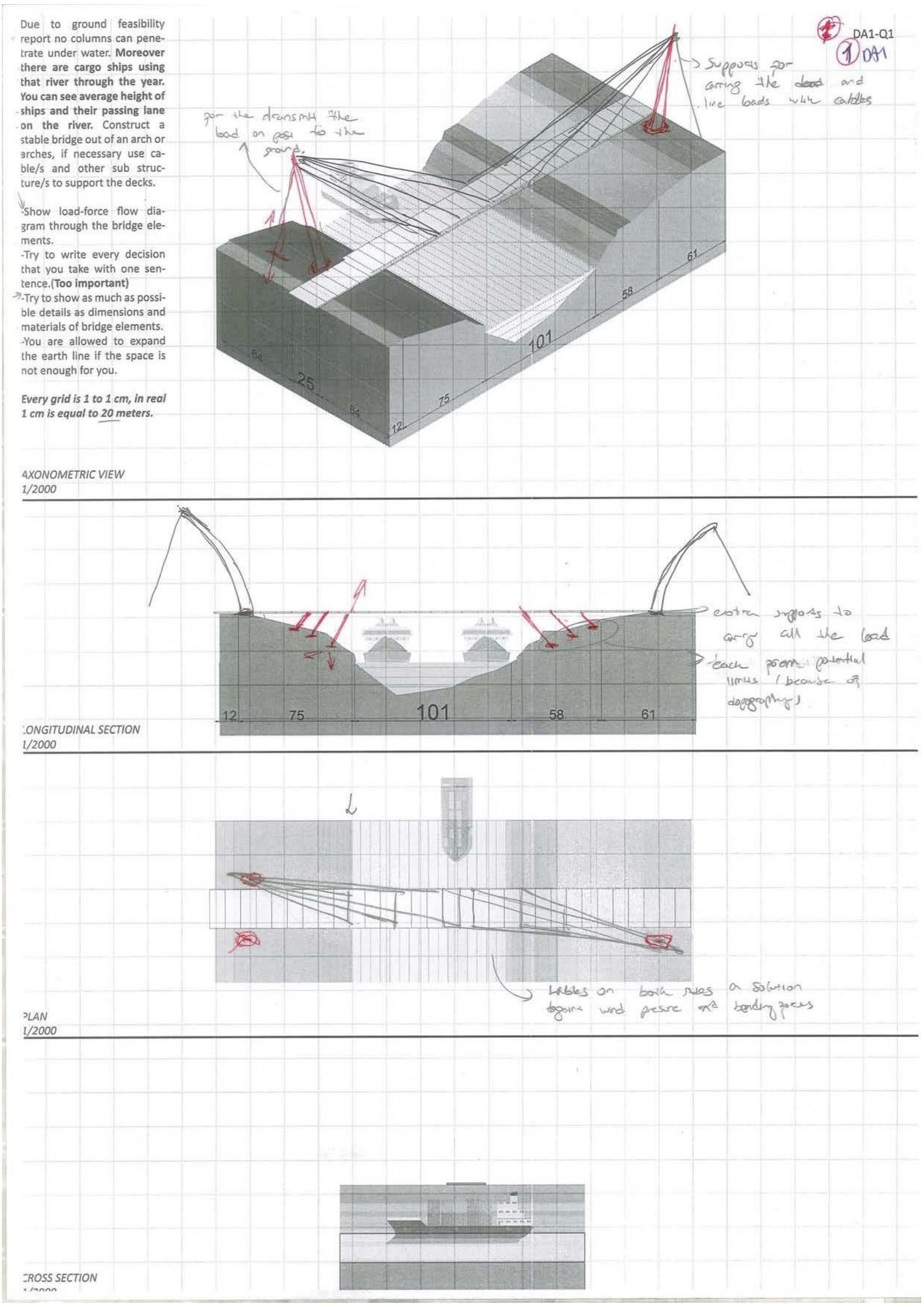

Figure 4.1. Participant 1 DA-1 Arch Bridge Question

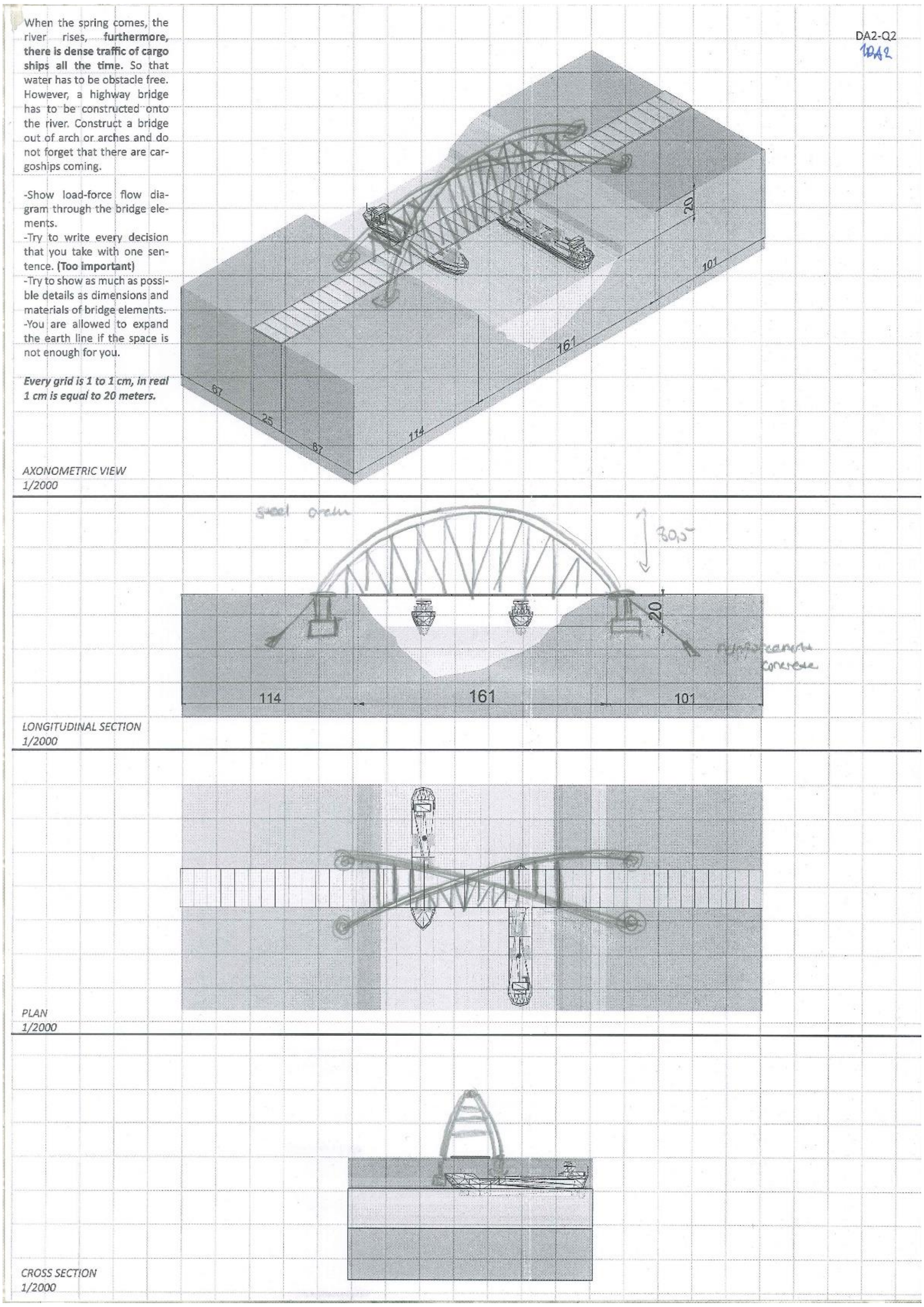

Figure 4.2. Participant 1 DA-2 Arch Bridge Question

In the first diagnostic assessment, since the student does not know arch bridge typology, the participant designed a double cable stayed bridge by using an "I" shaped pylons. Bridge is slightly stable, however using the cable arrangement is not an applicable one, because deck is rotating with that formation. No material is indicated. Moreover, the student is aware that the bridge needs foundations, however does not know how to design a separate one. Since the student does not recognize the arch bridge topology the level of the student is indicated as prestructural.

However, after having SPVR education student shows important development in the second diagnostic assessment. In DA-2, the participant designed a through double arch bridge by crossing two major arches and supporting them by horizontal bracings. The bridge is a very stable one in terms of all the relations between the structural elements as cables, arches and foundations. Moreover, the participant uses different and detailed elements than shown in StructurePuzzleVR which is an innovative improvement can only be seen in extended abstract level. Arch is made out of steel and 7 meters thick crossed steel solid arches for 161 meters main span are shown. Designing crossed steel cables as a supporter between the arch and the deck also a feature of extended abstract. Moreover, a very detailed separate foundations are shown and a simple flow of forces is given. Because of these innovative improvements in participant’s design; the level is increased from prestructural to extended abstract.

Table 4.5. *Arch-Bridge Results of P-01*

	Participant Number	P-01 1-DA1	P-01 2-DA2
	Is it an arch bridge?	Since the student does not know arch bridge typology, the participant designed a double cable cable stayed bridge by using an "I" shaped pylons	The participant designed a through double arch bridge by crossing two major arches and supporting them by horizontal bracings
	Is the Bridge Stable?	Bridge is slightly stable, however using the cable arrangement is not a applicable one, because deck is rotating with that formation	The bridge is a very stable one in terms of all the relations between the structural elements as cables, arches and foundations. Moreover, the participant uses different and detailed elements than shown in StructurePuzzle VR
Design of Arch/es	**Material**	No material is indicated	Arch is made out of steel
	Elaboration on Arch Section Dimensions of Arches Using Minor Support Elements	(NA) No arches are designed	7 meters thick crossed steel solid arches for 161 meters main span are shown
	Height/Main Span Ratio	No arches are designed	0.5
Design of Minor Support Elements	**Design of Minor Support Elements (Steel Cables, Trusses etc.)**	(NA)	Designing crossed steel cables as a supporter between the arch and the deck
	Middle Supports Between Arches (Against Horizontal Loads)	(NA)	Designing cross steel beams between the arches
	Foundations	Indicated a simple foundation. Student is aware that the bridge has foundations, however does not know how to design a separate one.	A very detailed separate foundations are shown.
	Flow of Forces	Student is aware the flow of forces through pylons and the other parts	A simple flow of forces is given
Level of Understanding		PRESTRUCTURAL	EXTENDED ABSTRACT

Participant 2 – SPVR- Arch Bridge – (Prestructural to Extended Abstract)

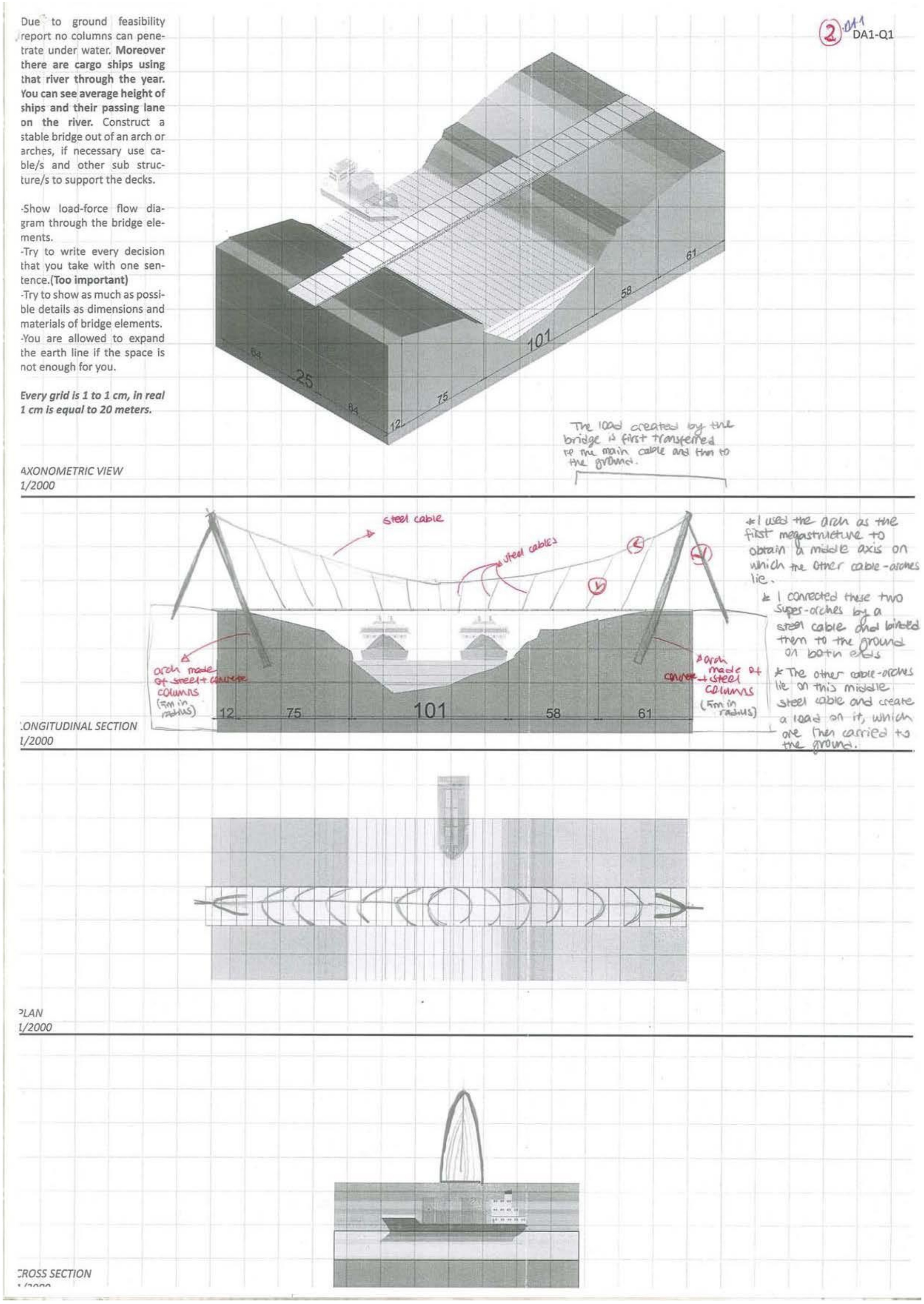

Figure 4.3. Participant 2 DA-1 Arch Bridge Question

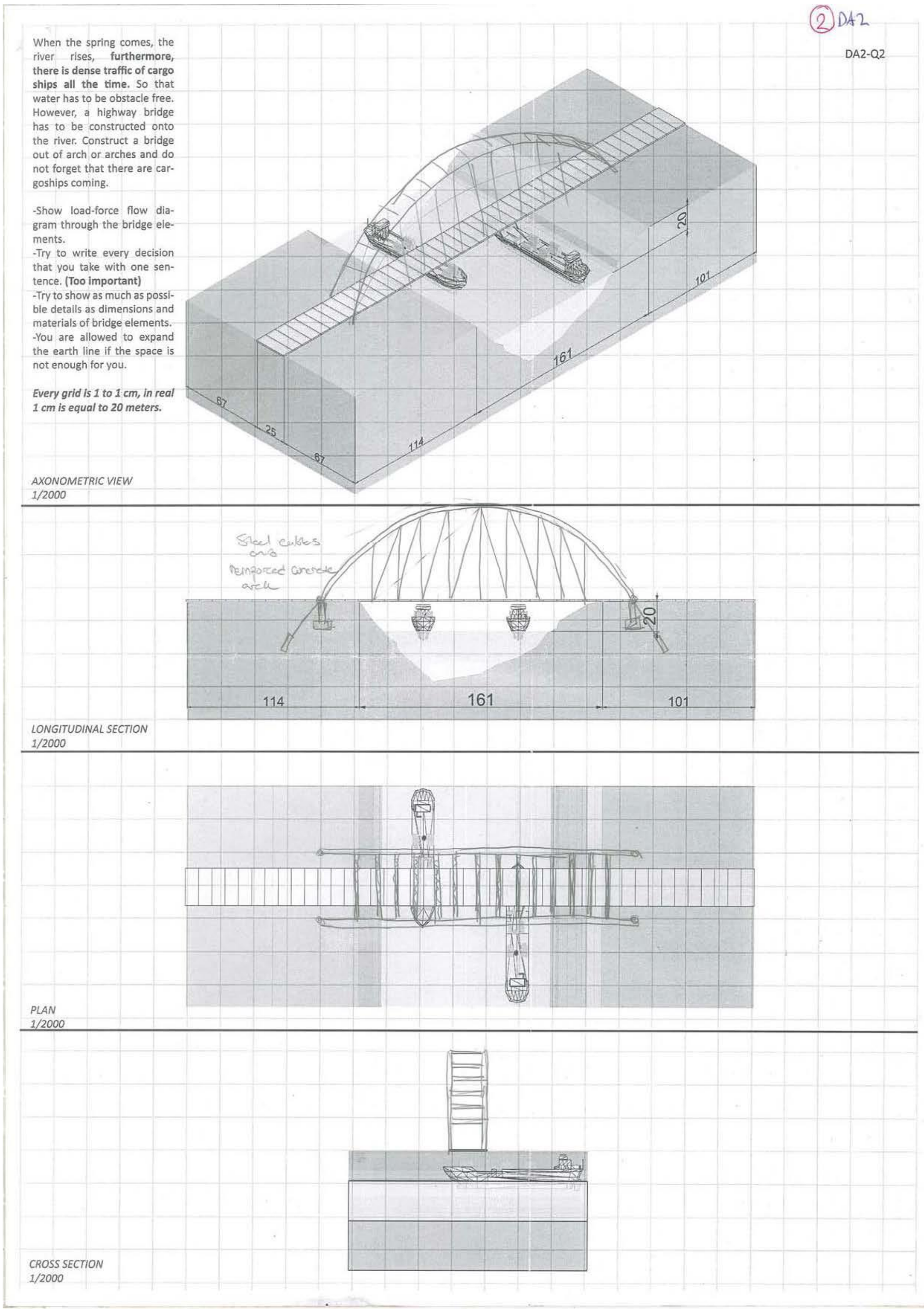

Figure 4.4. Participant 2 DA-2 Arch Bridge Question

In the first diagnostic assessment, since the student does not know the arch bridge typology, the participant designed a mono-cable suspended bridge by using an arch shaped pylon. Bridge is slightly stable, however using two-legged cable coming out of one main cable makes the bridge less stable against lateral loads. Pylons are made out of concrete and steel. Student is aware that the bridge has to have foundations, however does not know how to design a separate one. A detailed flow of forces is given. As a result, not designing the required bridge topology set the level of the student as prestructural.

There are notable developments according to DA-2. Participant designed a double arched bridge by combination of the cross-steel cable formation. The bridge is a very stable one in terms of all the relations between the structural elements as cables, arches and foundations. Moreover, the participant uses different and detailed elements than shown in StructurePuzzle VR which is an innovative detail labelled as an extended abstract improvement. Arch is made out of reinforced concrete, moreover, arch section is a 5-meter-thick solid one not enough for a RC arch. Designing crossed steel cables as a supporter between the arch and the deck as minor supporting elements. The space between the arches are supported with horizontal steel beams. Furthermore, a very detailed separate foundation is shown as an extended abstract feature. Designing the arch bridge with various innovative details increased level of student from prestructural to extended abstract.

Table 4.6. *Arch-Bridge Results of P-02*

	Participant Number	P-02 1-DA1	P-02 2-DA2
	Is it an arch bridge?	Since the student does not know arch bridge typology, the participant designed a monocable suspended bridge by using an arch shaped pylons	The participant designed a double arched bridge by combinating the cross steel cable formation in the StructurePuzzleVR
	Is the Bridge Stable?	Bridge is slightly stable, however using two legged cable coming out of one main cable makes the bridge less stable against lateral loads	The bridge is a very stable one in terms of all the relations between the structural elements as cables, arches and foundations. Moreover, the participant uses different and detailed elements than shown in StructurePuzzle VR
Design of Arch/es	**Material**	Pylons are made out of concrete+steel	Arch is made out of reinforced concrete
Design of Arch/es	**Elaboration on Arch Section Dimensions of Arches Using Minor Support Elements**	(NA) No arches are designed Pylon section is a 5 meter thick solid one, enough for 100 meters span	Arch section is a 5 meter thick solid one not enough for a RC arch. Using crossed steel cables to hold the deck
Design of Arch/es	**Height/Main Span Ratio**	No arches are designed	The ratio is close to semi circle 0.4
Design of Minor Support Elements	**Design of Minor Support Elements (Steel Cables, Trusses etc.)**	(NA)	Designing crossed steel cables as a supporter between the arch and the deck
Design of Minor Support Elements	**Middle Supports Between Arches (Against Horizontal Loads)**	(NA)	The space between the arches are supported with horizontal steel beams
	Foundations	Indicated a simple foundation. Student is aware that the bridge has foundations, however does not know how to design a separate one.	A very detailed separate foundation is shown.
	Flow of Forces	A detailed flow of forces is given	Flow of forces is not given however it seems that student know what he is doing
	Level of Understanding	PRESTRUCTURAL	EXTENDED ABSTRACT

Participant 3 – SPVR- Shorter Span Cable-Stayed, Suspension Bridge – (Multistructural to Extended Abstract)

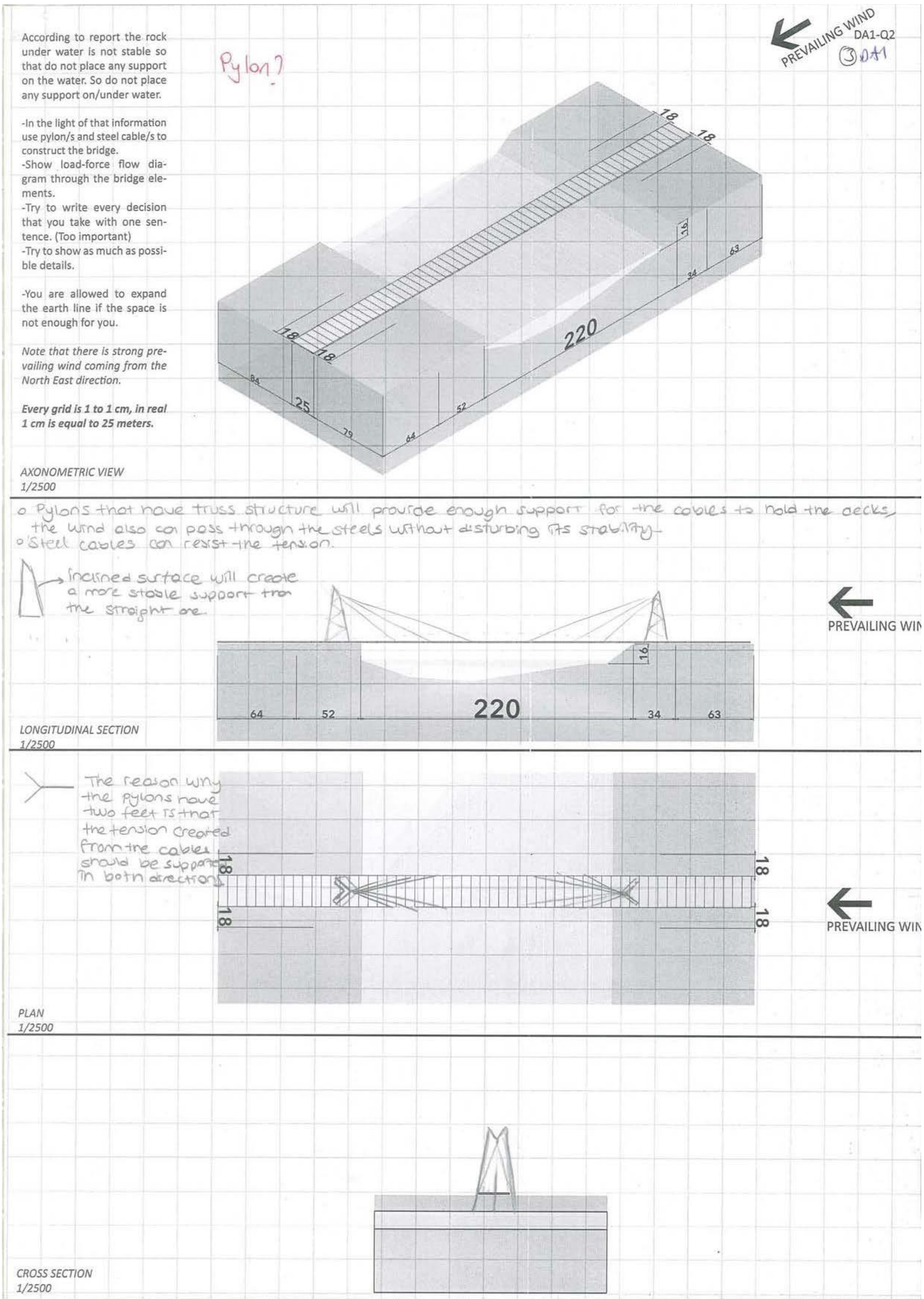

Figure 4.5. Participant 3 DA-1 Shorter-Span Bridge Question

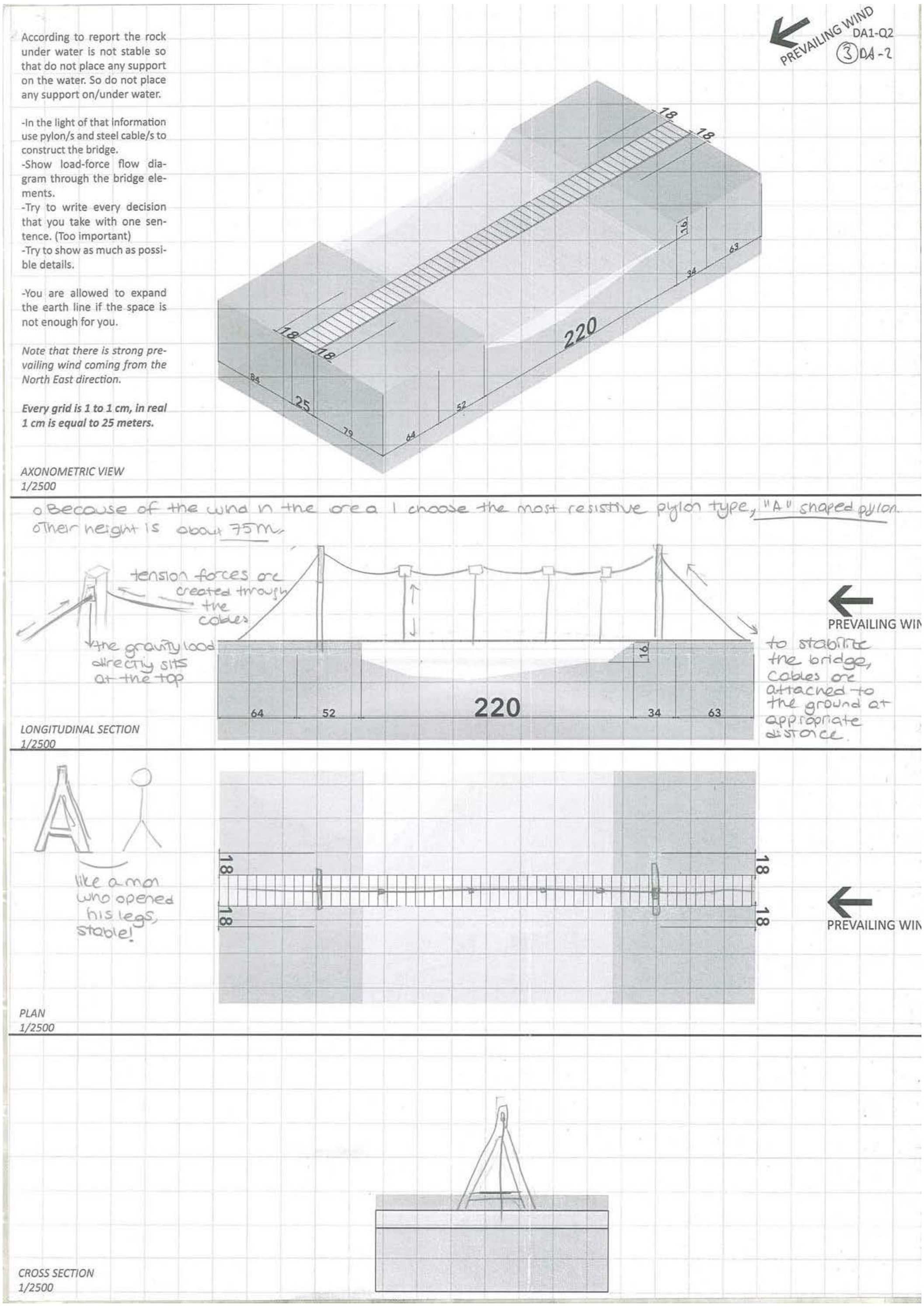

Figure 4.6. Participant 3 DA-2 Shorter-Span Bridge Question

The participant has designed cable-stayed bridge designed out of two triangle cross sectioned pylons. Even though the ratios of elements are looking insufficient the bridge is looking stable. Material is not indicated and thicknesses of pylons are shown as lines. Moreover, two legged inclined pylons are designed to have less weight and more stability. The steel cables are in modified-fan type formation. However, the cables are not meeting at the middle of the main span which makes the bridge less stable. Furthermore, steel cables are not present there is no side span, therefore the structure is not stable. Although the student knows and designs the required basic pieces of the cable-stayed bridge; they are not in a relation to support each other. Hence, the level of the student is determined as multistructural.

After having VR education, there were significant improvements in every aspect of the student's design in second diagnostic assessment. In DA-2, the participant has designed mono-cable suspension bridge designed out of “A” type pylons. One leg of the pylon thickness is 10 meters for passing 220 meters of main span. The participant draws all the specification of a pylon even by drawing details of it, which is and extra data not shown in SPVR. S/he preferred to design “A” type pylons to have more hollow section against the wind to penetrate freely and to have more compact structure. Moreover, using integrated main cable, suspender cables and anchoring them to a foundation buried underground which is an extended abstract feature. S/he indicates all the flow of forces as diagrams and in a written format. Since the participant adds addition details and is able to form her/his priori knowledge with the information involved in SPVR, the level of the student is increased to extended abstract.

Table 4.7. *Shorter Span Cable-Stayed, Suspension Bridge Results of P-03*

	Participant Number	P-03 1-DA1	P-03 2-DA1
	Is It a Cable-Stayed or a Suspension Bridge?	Cable-stayed bridge designed out of two triangle cross sectioned pylons	Mono-cable suspension bridge designed out of two triangle cross sectioned pylons
	Is the Bridge Stable?	Even though the ratios of elements are looking insufficient the bridge is looking stable	Bridge is a very stable one
Design of Pylon/s	**Material**	Material is not indicated	Material is not indicated
	Elaboration on Pylon/s Cross Sections	-Thicknesses of pylons are shown as lines -The pylons are out of triangular trusses -Designing inclined surface instead of a straight one -Designing pylons as two legged pylons to have less weight and more stability	One leg of an "A type pylon" thickness is 10 meters for 220 meters of main span. The participant draws all the specificationf of a pylon even giving a detail
	Pylon Height/Main Span Ratio	0.15	0.35
	Cautions Against Windload	Using triangular trussed pylons to have more hollow section against the wind to penetrate freely.	Using A type pylons to have more hollow section against the wind to penetrate freely and to have more compact structure.
Design of Minor Support Elements	**Main Span**	-The steel cables are in modified-fan type formation -However the cables are not meeting at the middle of the main span	-Using integrated main cable and suspender cables
	Side Span	Steel cables are not present, therefore the structure is not stable	Steel cables are added and anchored to a foundation buried underground
	Side Span/Main Span Ratio	There is no side span and the structure is not stable because of that reason	0.3 According to participant's notes, she is conscious about the ratio of side span/main span
	Foundations of Pylons	Is not indicated	The participant is aware that the structure needs foundation by showing bottom part of the pylons underground
	Flow of Forces	A simple flow of forces is given	The participant indicates all the flow of forces as diagrams and in a written format
Level of Understanding		**MULTISTRUCTURAL**	**EXTENDED ABSTRACT**

Participant 4 – SPNotes- Shorter Span Cable-Stayed, Suspension Bridge – (Multistructural to Multistructural)

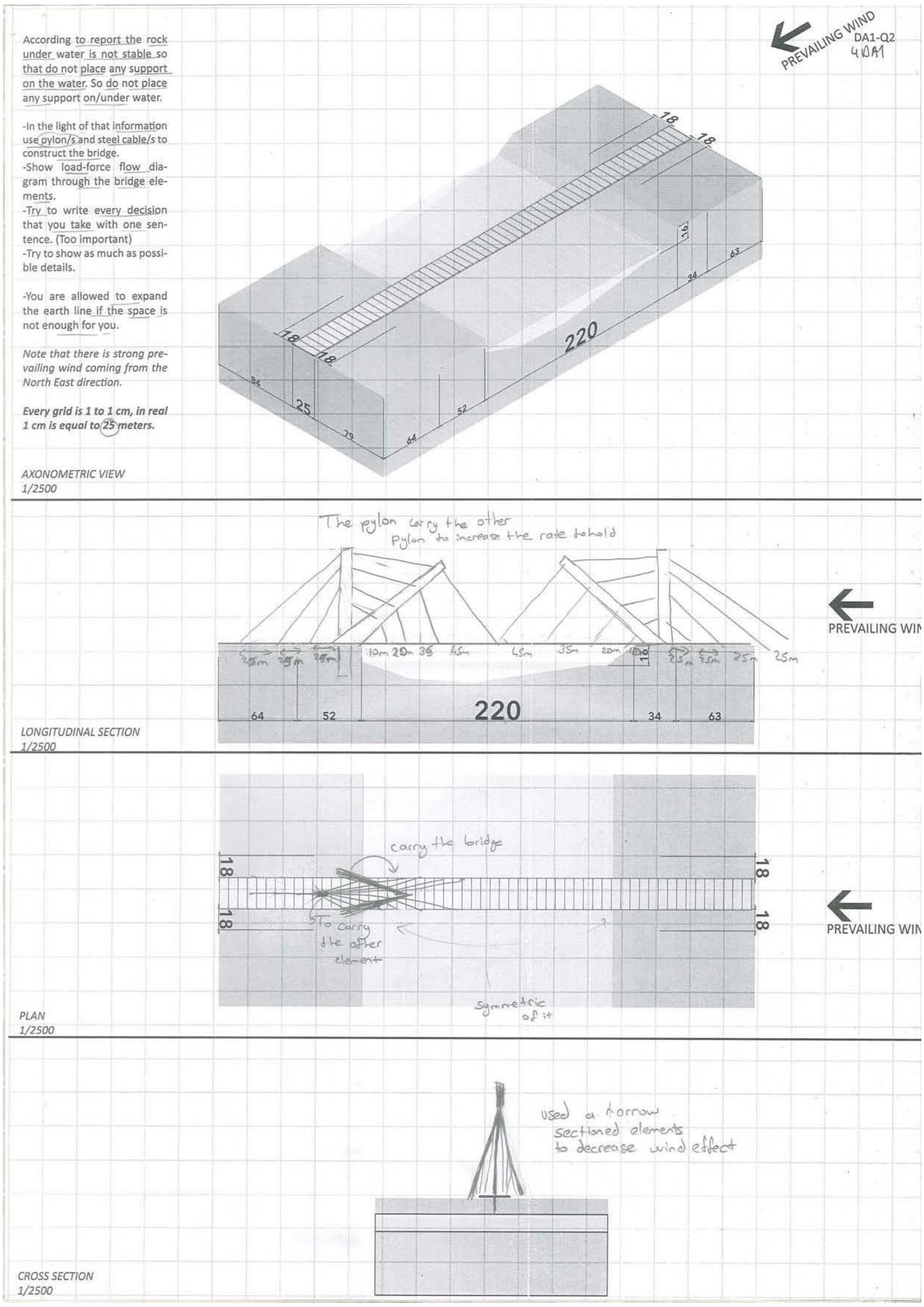

Figure 4.7. Participant 4 DA-1 Shorter-Span Bridge Question

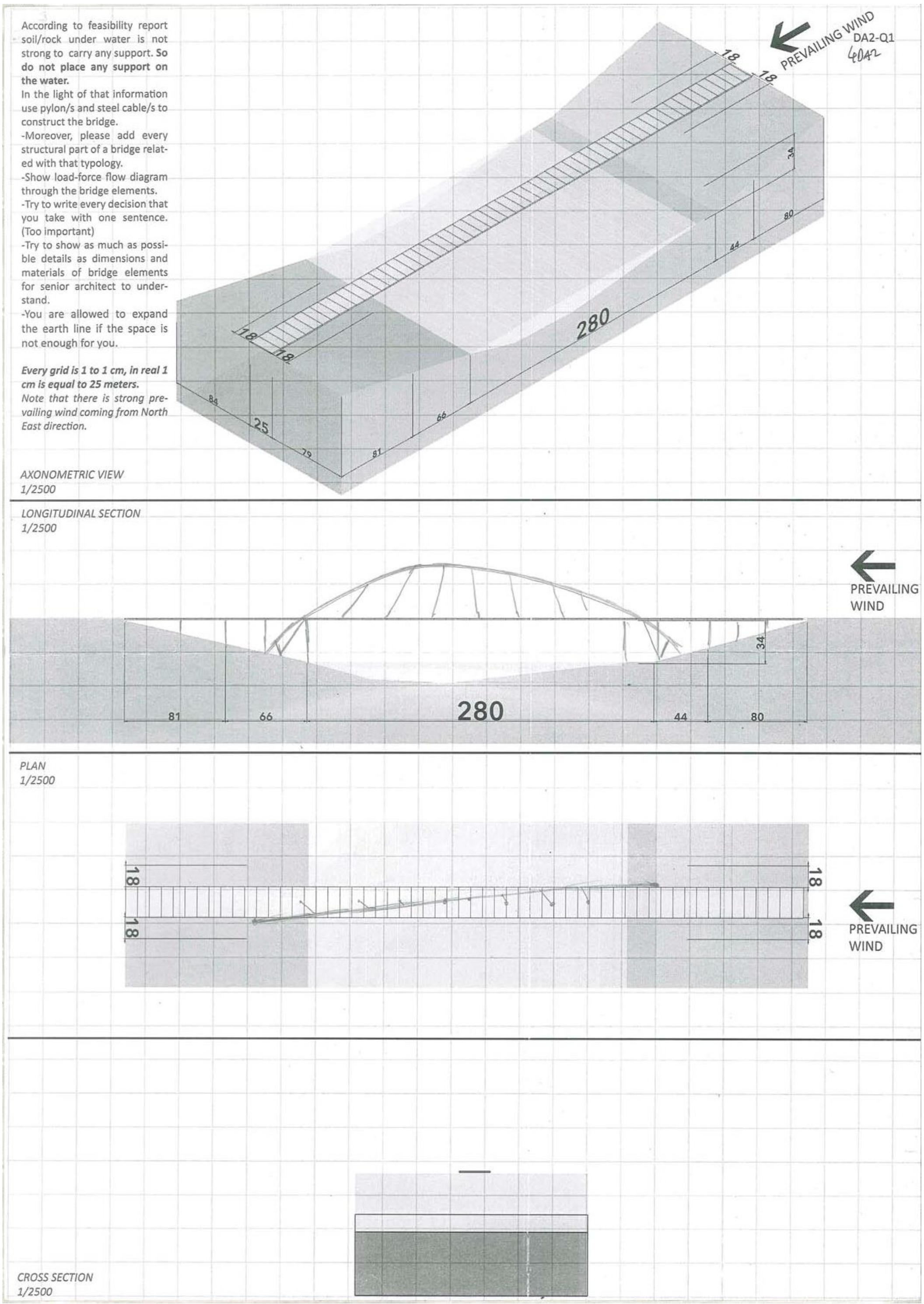

Figure 4.8. Participant 4 DA-2 Shorter-Span Bridge Question

In the first assessment the participant has designed cable-stayed bridge designed out of four straight and front-inclined sectioned pylons. However, there might be over-design of mega elements and front-inclined towers cannot be structurally stable. Sections of pylons are given with an appropriate thickness, yet the cross sections of pylons are drawn as lines without any thicknesses. The student designs with "inverted Y" type pylons to have more hollow section against the wind to penetrate freely. The steel cables are in harp type and meeting at the middle of the main span, in addition to that, exact distances between anchorages are given. Although the bridge has all the basic parts related to a bridge structure, there are problems while constructing relations between these parts, which leaves the level of student as multistructural.

In the second assessment, the participant has designed a through-mono arch bridge which cuts all the span with a crossing angle. Since, the student design is not in the frame of the question is asked, namely not designing with pylons and steel cables the level of the student is determined as prestructural. However, other parameters of the bridge, such as thicknesses and material usage are worth analyzing to understand whether the student is developed or not after SPNotes. Regarding that, not specifying material and showing thickness of the arch as lines shows that there are no observed improvements in these parameters as well.

Table 4.8. *Shorter Span Cable-Stayed, Suspension Bridge Results of P-04*

	Participant Number	P-04 1-DA1	P-04 2-DA2
	Is It a Cable-Stayed or a Suspension Bridge?	Cable-stayed bridge designed out of four straight and front-inclined sectioned pylons	A through mono arch bridge which cuts all the span with an angle
	Is the Bridge Stable?	There might be over-design of mega elements -Front-inclined towers cannot be structurally stable	The bridge is very stable, however there are couple of problems
Design of Pylon/s	**Material**	Material is not indicated	Material is not indicated
	Elaboration on Pylon/s Cross Sections	-Sections of pylons are given with an appropriate thickness -However cross sections of pylons are drawn as lines	Pylons are given as lines The cross section and the height of pylons are not enough to have a stable structure
	Pylon Height/Main Span Ratio	0.33	0.1
	Cautions Against Windload	Using "inverted Y" type pylons to have more hollow section against the wind to penetrate freely.	No cautions against windload
Design of Minor Support Elements	**Main Span**	-The steel cables are in harp type and meeting at the middle of the main span -A detailed distance between anchorages are given	(NA)
	Side Span	The steel cables are in harp type.	(NA)
	Side Span/Main Span Ratio	0.75	(NA)
	Foundations of Pylons	Is not indicated	The participant is aware that the structure needs foundation merging bottom part of the arch an another solid element
	Flow of Forces	A simple flow of forces is given	No flow of forces is given
Level of Understanding		**MULTISTRUCTURAL**	**PRESTRUCTURAL**

Participant 9 – SPVR- Longer Span Suspension, Cable Stayed Bridge– (Multistructural to Relational)

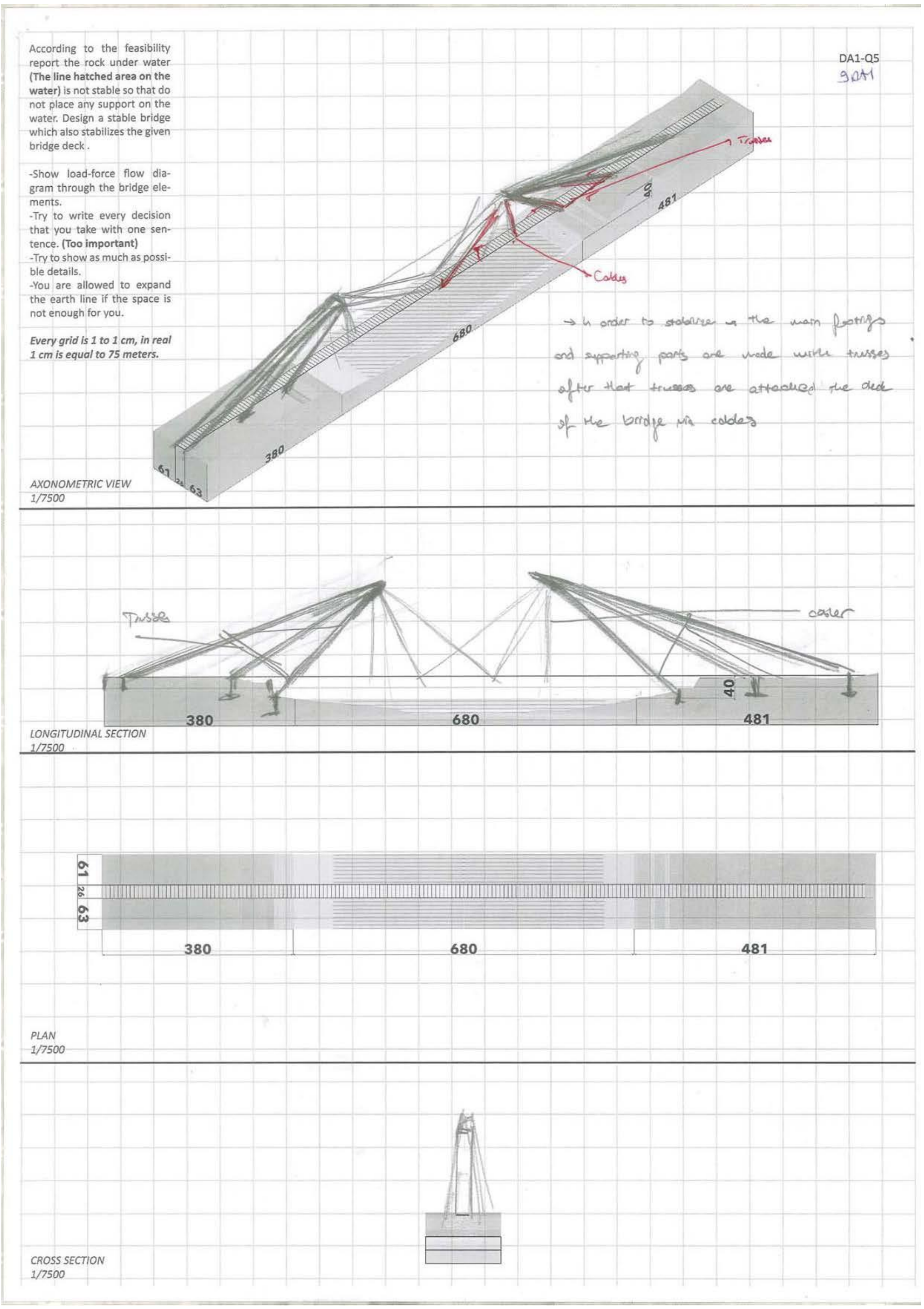

Figure 4.9. Participant 9 DA-1 Longer-Span Bridge Question

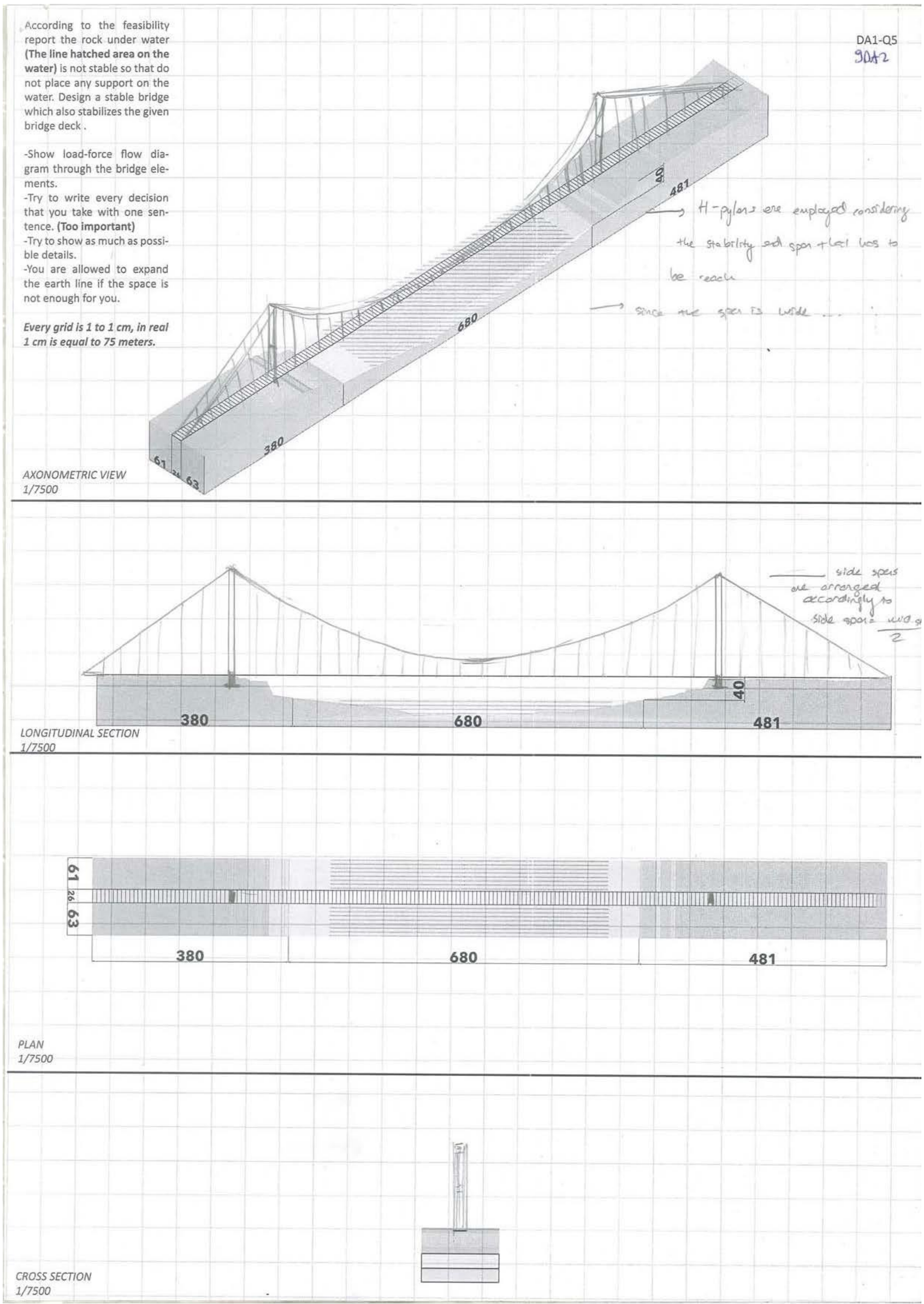

Figure 4.10. Participant 9 DA-2 Longer-Span Bridge Question

The participant has designed a cable-stayed bridge composed of two front-leaning pyramidal shape pylons with double-cable for the first diagnostic assessment. The front-leaning pylons are excessively inclined to not carry themselves. The participant is aware that there are complex arrangements of pylons, however the sections of pylons are given as lines without any thickness. Steel cables are used, but the cables are placed as if they are working against compression loads. Furthermore, detailed foundations and flow of forces in a written format are given. Since the bridge has all the basic components in itself, but the relations are not strongly constructed in order to have a stable bridge the level of the student remains at multistructural.

There are significant improvements on student's design after having SPVR. The participant has designed a suspension bridge composed of two very detailed 25 meters thick "H" type pylons. Using more hollow pylon types against wind to pass through is contributing to structural stability. The participant is aware that cables have to be in specific distance to each other, which is a data not taught in SPVR. Fan formation of multiple steel cables are composing one side span. However, stiff foundation for anchorage is not shown. Furthermore, detailed foundations and flow of forces in a written format are given. Due to neat detailing and dimensioning of the bridge solution not shown in SPVR, the level of the student is increased to extensive abstract.

Table 4.9. *Longer Span Suspension, Cable-Stayed Bridge Results of P-09*

	Participant Number	P-09 1-DA1	P-09 2-DA1
	Is It a Cable-Stayed or a Suspension Bridge?	Double-cable cable-stayed bridge designed out of four inclined pylons	Cable-stayed bridge designed out of two H type pylons with horizontal bracing between them
	Is the Bridge Stable?	The structure is stable	The structure is stable
Design of Pylon/s	**Material**	Material is not indicated	Material is not indicated
	Elaboration on Pylon/s Cross Sections	-Two H type pylons are designed -Bracings on H type pylons are adding another level of structural stability against lateral loads -However the height of pylons are not sufficient	-Two H type pylons are designed -The height of pylons are around being optimal. -
	Pylon Height/Main Span Ratio	0.2	0.5
	Cautions Against Windload	Using H type pylons to have more hollow section against the wind to penetrate freely. (Daha önce görülmedi)	Using H type pylons to have more hollow section against the wind to penetrate freely.
Design of Minor Support Elements	**Main Span**	-The steel cables are in fan type formation -The cables are meeting at the middle of the main span and crossing with each other (Daha önce görülmedi)	-The steel cables are in fan type formation -The cables are meeting at the middle of the main span
	Side Span	-Just two steel cables are added on one side span. -The steel cables are in fan type formation	Steel cables are added and anchored to a foundation however anchorage foundations are not shown buried underground
	Side Span/Main Span Ratio	0.15	0.5 According to participant's notes, she is conscious about the ratio of side span/main span
	Foundations of Pylons	A simple pile foundation is indicated	A simple pile foundation is indicated
	Flow of Forces	She indicates all the flow of forces as diagrams and in a written format	She indicates all the flow of forces in a written format
Level of Understanding		**RELATIONAL**	**EXTENDED ABSTRACT**

Participant 5 – SPNotes- Longer Span Suspension, Cable Stayed Bridge – (Unistructural to Relational to Extended Abstract)

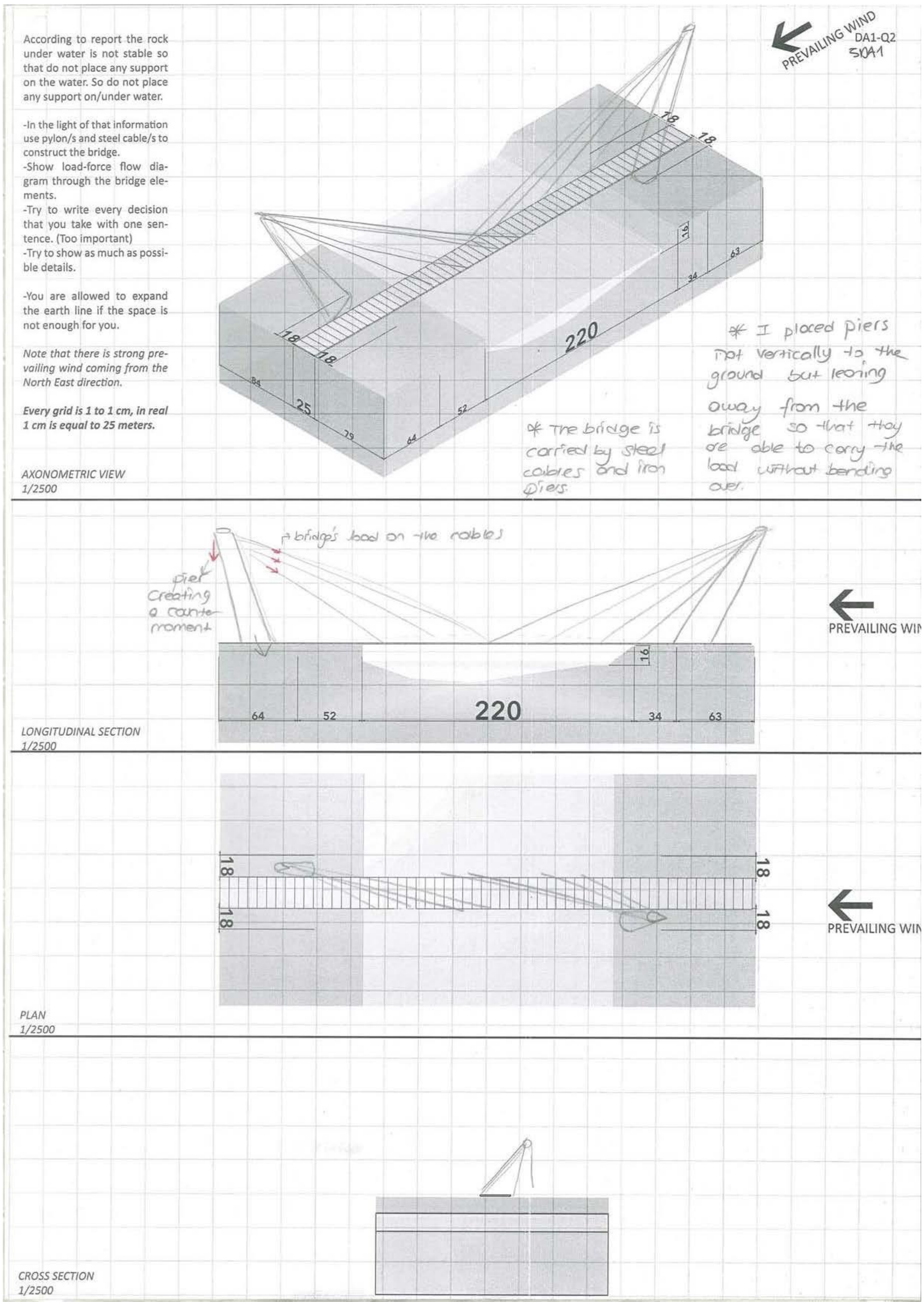

Figure 4.11. Participant 5 DA-1 Shorter-Span Bridge Question

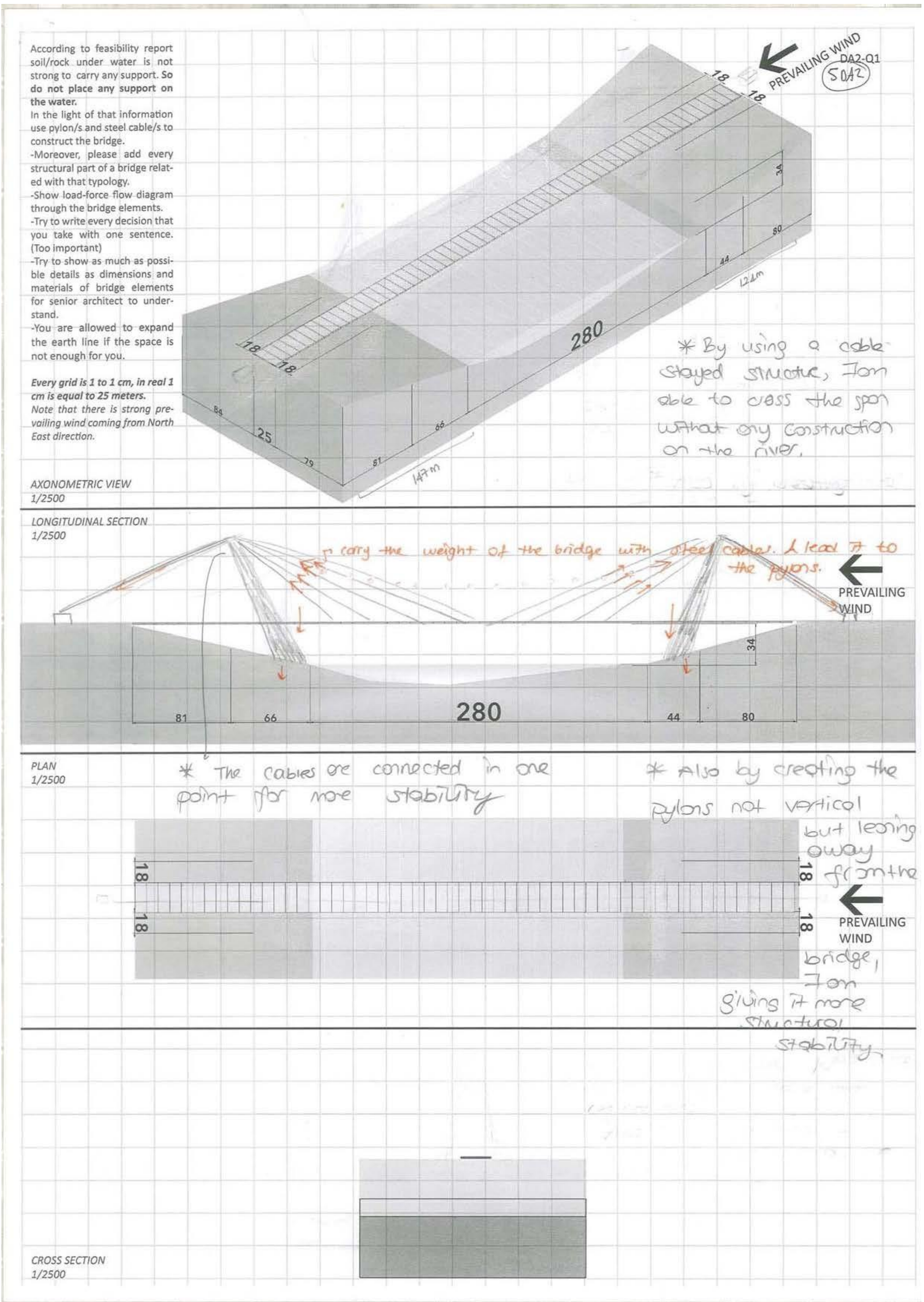

Figure 4.12. Participant 5 DA-2 Shorter-Span Bridge Question

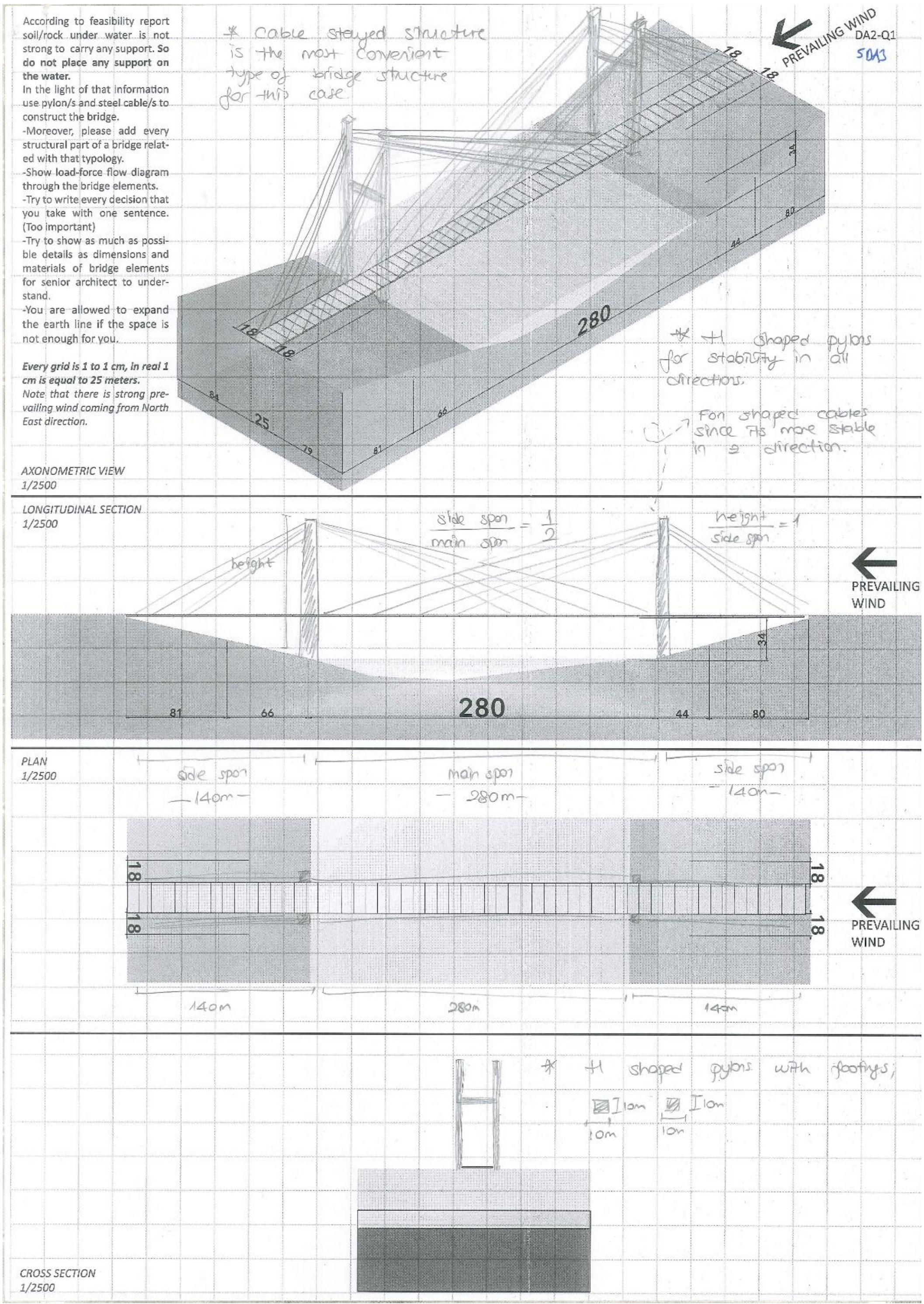

Figure 4.13. Participant 5 DA-3 Shorter-Span Bridge Question

To understand the benefits of the application in regular use, Participant 5 received two SPVR training sessions one month apart and three diagnostic assessments were performed. As a result, it was observed that the student was able to remember his / her previous knowledge acquired in SPVR better and focus more on the details in the virtual reality education. Regular development of the student in the suspension bridge question can be a data supporting the positive effects of regular use of SPVR.

In DA-1, the participant designed a through double arch bridge integrated with steel cables and crossed arches. Two 15 meters thick intersected arches through 680 meters are not stable for that bridge, moreover no specific material and caution against lateral wind load is taken. Using the wrong type of megastructure not indicated in the question makes the level of student as prestructural for that case.

In DA-2, the student has designed double-cable suspension bridge composed of two “A” type pylons. In addition to use “A” type pylons, the sections of pylons are getting thinner from bottom to top, 15 to 30 meters respectively. In this assessment the student shows her/his awareness against the wind load by using more hollow pylon types against wind to pass through. However, foundations are not indicated but the reflected forces coming from foundations are shown. More than solely designing parts of the bridge, at this stage student is able to relate components in a way to have structural stability. These decisions taken by the student sets her/his level as relational.

After having second SPVR education in one month apart, student is taken into the third diagnostic assessment. In that stage, s/he has designed double-cable suspension bridge composed of two tapered steel “A” type pylons. Furthermore, indicating steel pylons, cables, deep detailed concrete foundations and drawing details of pylon foots which indicates one foot is 15*15 meters for 680 meters of main span has taken the student to extended abstract level.

Table 4.10. . *Short-Span Bridge Structure Results of P-05*

	Participant Number	P-05 1-DA1	P-05 2-DA2	P-05 3-DA2
	Is It a Cable-Stayed or a Suspension Bridge?	Cable-stayed bridge designed out of two back-leaning solid pylons	Cable-stayed bridge designed out of two back-leaning solid pylons	Cable-stayed bridge designed out of two 10*10 meters H type solid pylons
	Is the Bridge Stable?	Although there are problems regarding stability, the bridge is stable	Although there are problems regarding stability, the bridge is stable	The bridge is very stable
Design of Pylon/s	**Material**	Steel cables and iron pylons	Material is not indicated	Steel pylons and cables are indicated
	Elaboration on Pylon/s Cross Sections	Sections of pylons are getting thinner from bottom to the top, from 20 meters to 10 meters	Sections of pylons are getting thinner from bottom to the top, from 20 meters to 10 meters	Double 10*10 meters steel H type solid pylons against lateral and windloads that the participant indicated especially
	Pylon Height/Main Span Ratio	0.2	0.35	0.35
	Cautions Against Windload	No specific application against windload	No specific application against windload	Designing hollow sectioned pylons against the windload
Design of Minor Support Elements	**Main Span**	-The steel cables are in modified-fan type formation -The cables are meeting at the middle of the main span -However the deck can be rotated due to moment resulted from the locations that cables are anchored	-The steel cables are in modified-fan type formation -Moreover the participant explained the reason to use that particular cable arrangement -The cables are meeting at the middle of the main span	-The steel cables are in fan type formation -Moreover the participant explained the reason to use that particular cable arrangement -The cables are meeting and passing through the middle of the main span
	Side Span	No need for side span	Steel cables are added and anchored to a concrete foundation buried underground	Multiple cables are composing the side span in a fan formation
	Side Span/Main Span Ratio	No need for side span	0.35 The participant is aware that there has to be ratio between side/main span ratio	0.5 Student is aware that there has to be ratio between side/main span ratio
	Foundations of Pylons	Is not indicated but shows the reflected forces coming from foundations	Is not indicated but shows the reflected forces coming from foundations	Is not indicated but shows the reflected forces coming from foundations
	Flow of Forces	A detailed flow of forces is given	The participant indicates all the flow of forces as diagrams and in a written format	The participant indicates all the flow of forces as diagrams and in a written format
	Level of Understanding	**MULTISTRUCTURAL**	**RELATIONAL**	**EXTENDED ABSTRACT**

Participant 6 – SPNotes- Long-Span Covering Structure – (Unistructural to Unistructural)

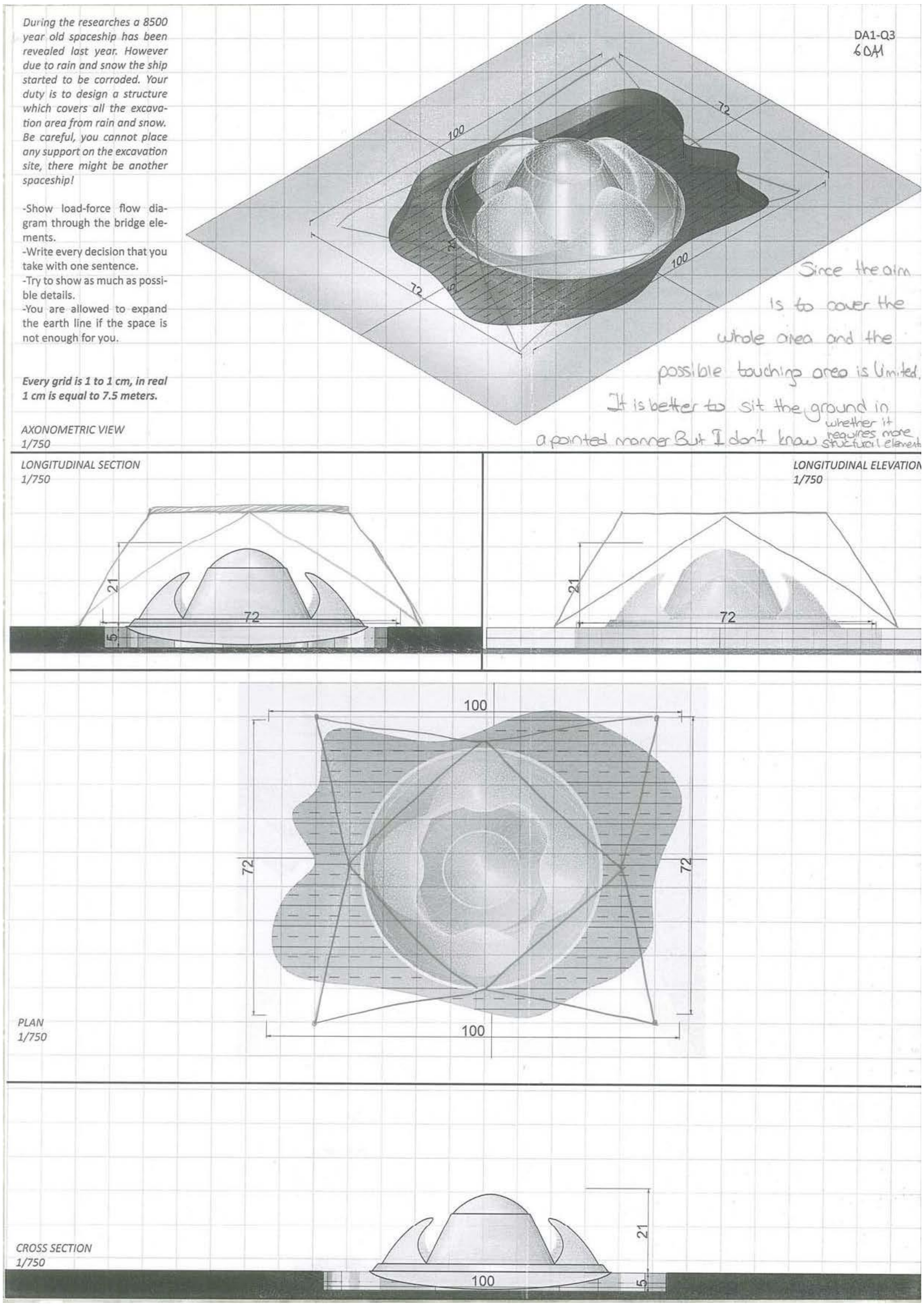

Figure 4.14. Participant 6 DA-1 Long-Span Covering Structure Question

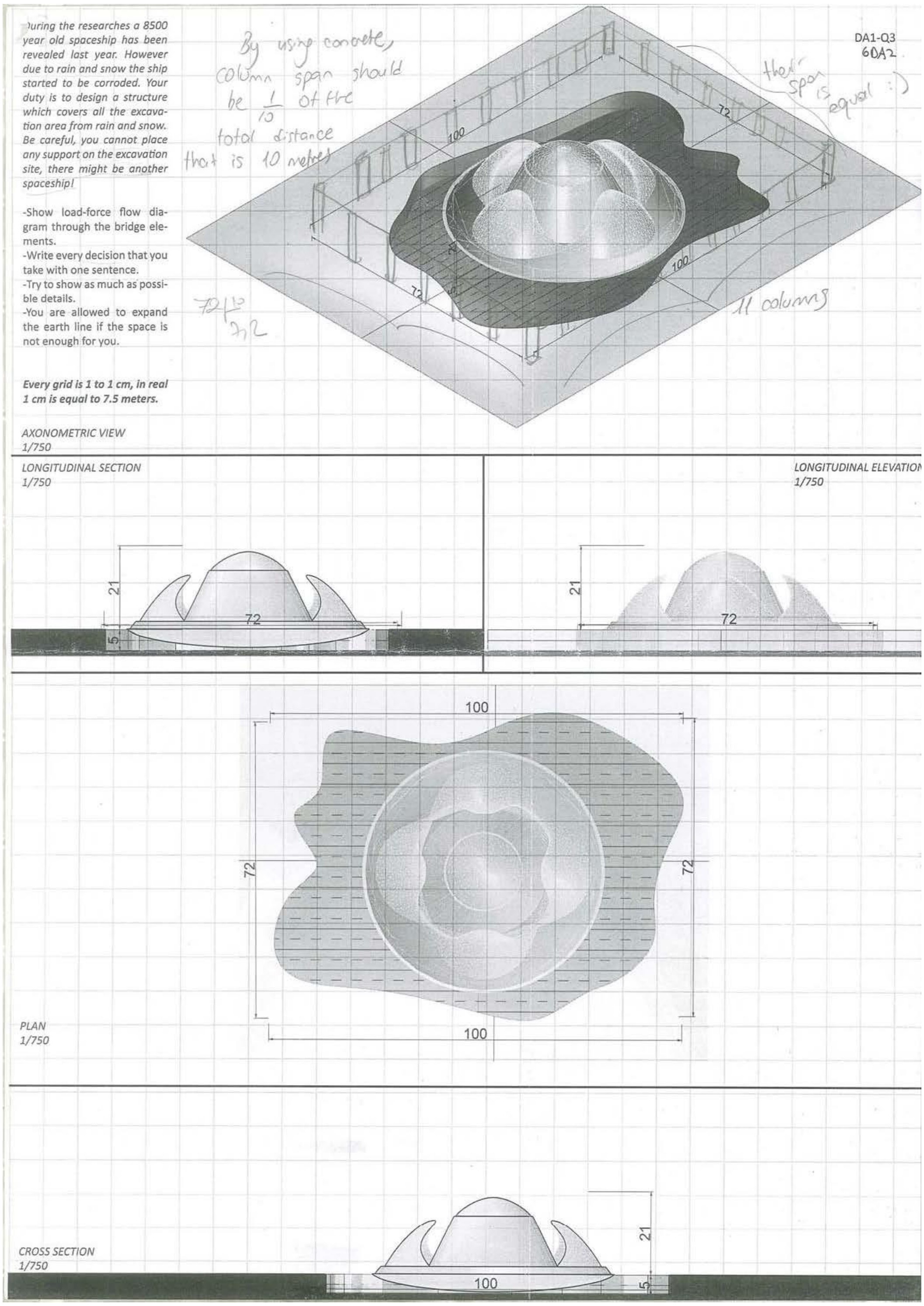

Figure 4.15. Participant 6 DA-2 Long-Span Covering Structure Question

Long span covering structure is a different question than the other long-span bridge questions. This time the participants are forced to leave their comfort zone and want them to test their new knowledge on this question.

Regarding that in DA-1, The participant uses steel elements and a slab, however -The structure is not stable; because the steel elements are too thin and the slab is not stabilized. Moreover, material is not indicated and no flow of forces is given. Using only one particular type of information but leaving design decisions related to dimensioning sets the level of the student to unistructural.

After having SPNotes education, the participant designs 10 meters height columns, however there is no indication of covering and material. There are 1x1 meters thick perimeter columns in every 10 meters, participant is aware of the ratio between span and column size but the height of columns is not enough to cover the spaceship. Similarly, to DA-1, the fact that even though student has appropriate decisions related to types of construction; not elaborating on dimensions of the structural parts determines the level of student as unistructural again.

Table 4.11. *Long-Span Covering Structure Results of P-06*

	Participant Number	P-06 1-DA1	P-06 2-DA2
	The Type of the Structure	The participant uses steel elements and a slab	Student uses 10 meters height columns however there is no indication of covering
	Is the Structure Stable?	-The structure is not stable -The steel elements are too thin -The slab is not stabilized	Since there is no covering on top of it this question cannot be answered
Design of Megastructure/s	**Material**	Material is not indicated	Material is not indicated
Design of Megastructure/s	**Design and Dimensions of Megastructure/s (Arches, Vertical Elements, Pylon Height/Main Span Ratio)**	-The steel elements are too thin and shown as lines	-There are 1x1 perimeter columns in every 10 meters, participant is aware of the ratio between span and column size -The height of columns are not enough to cover the spaceship -However, student could not come up with a covering idea which covers 100 meters
Design of Megastructure/s	**Design of Vertical Minor Support Elements**	No need for minor support elements	No need for minor support elements
Design of Megastructure/s	**Design of the Covering and Cautions Against Rain-Snowloads**	-Adding covering on top of the spaceship, however it is not stabilized	No covering on the spaceship
	Foundations of Megastructures	Is not indicated	Is not indicated
	Flow of Forces	No flow of forces is given	No flow of forces is given
	Level of Understanding	UNISTRUCTURAL	UNISTRUCTURAL

Participant 7 – SPVR- Long-Span Covering Structure– (Multistructural to Relational)

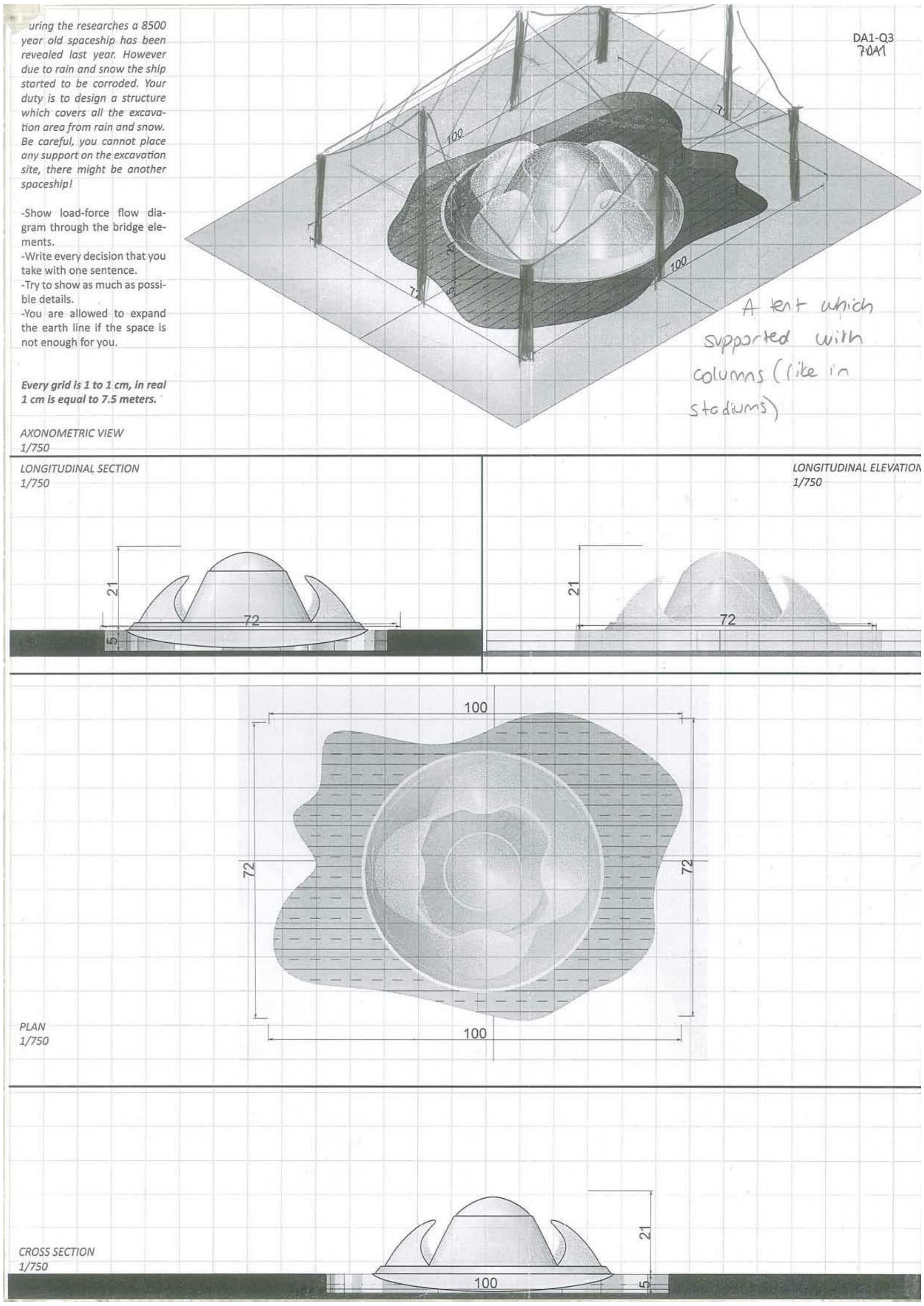

Figure 4.16. Participant 7 DA-1 Long Span Covering Structure Question

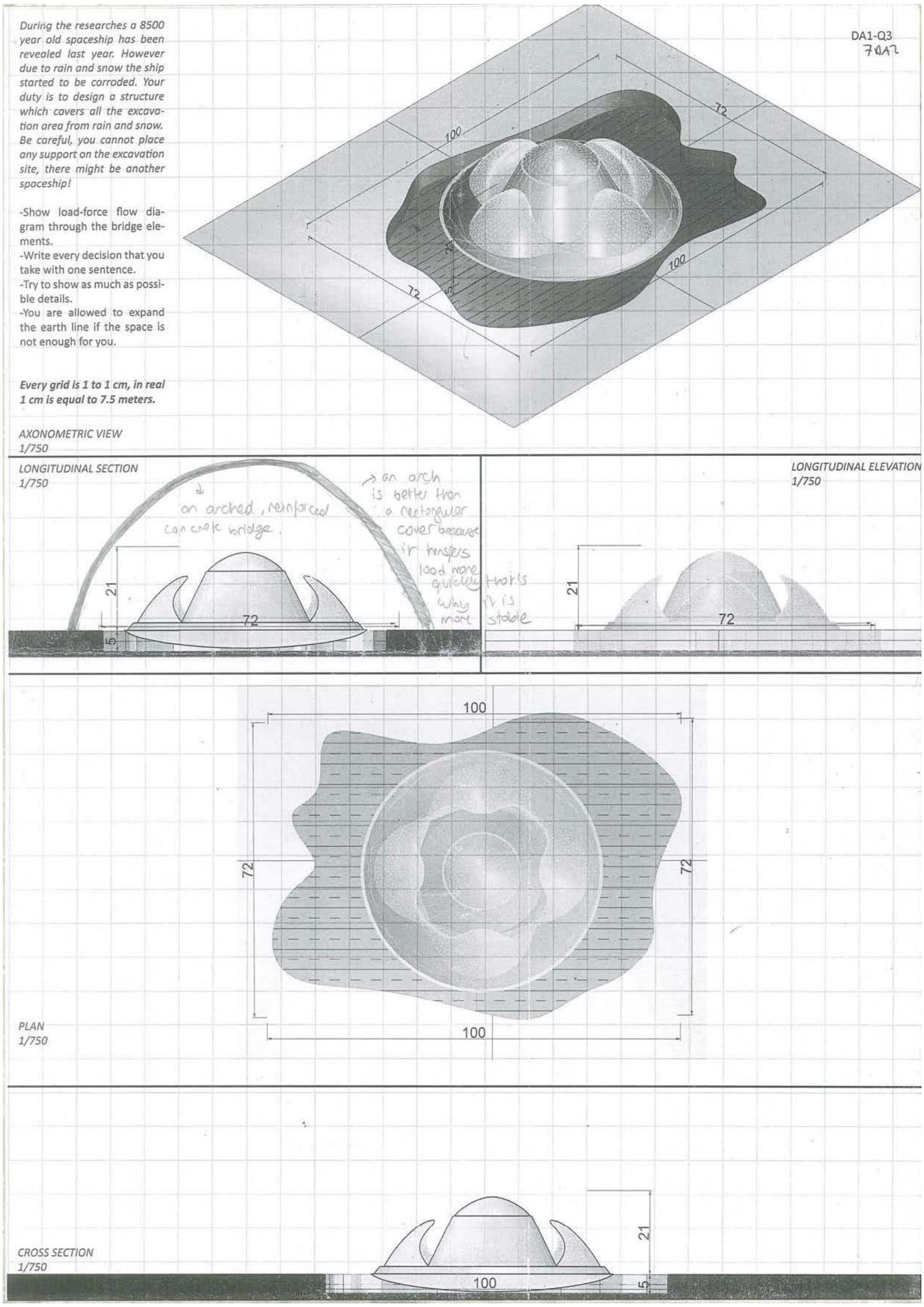

Figure 4.17. Participant 7 DA-1 Long Span Covering Structure Question

In DA-1, a tensile structure is designed by stretching a membrane between seven vertical RC and steel pylons in different heights. Structure is stable without any live loads on it, however, the membrane covering cannot carry the snow or rain load. Three meters thick pylons for passing 72 meters of main span are indicated. Student is aware the thicknesses, however is not aware of specific ratios of thicknesses with respect to other elements. There is no side span, therefore the stable cannot be well stabled, similarly, no foundations are drawn as anchorages. Student indicates simple flow of forces in a written format. Although student is able to think the components of the structure separately, not relating and foreseeing possible problems determines level of student as multistructural.

In DA-2, a solid reinforced concrete arch covering all 72x100 meters area is added. Since a quite similar structure is shown in SPVR education, student is able to reflect what s/he learnt in the training. Moreover, student designs the 80x35 meters arch for passing 80 of main span, which is near to optimal half arch. Besides covering the spaceship from rain and snow, vault shaped three meters thick solid reinforced concrete provides good water drainage. Student indicates all the flow of forces as diagrams and in a written format. In addition to solution in DA-1, indicating dimensions, materials and elaborating on sections, yet not providing an innovative solution, increase level of student from multistructural to relational.

Table 4.12. *Long-Span Covering Structure Results of P-07*

	Participant Number	P-07 1-DA1	P-07 2-DA1
	The Type of the Structure	A tensile structure tensed between seven vertical RC and steel pylons in different heights	A solid reinforced conrete arch covering all 72x100 meters area
	Is the Structure Stable?	Structure is stable without any live loads on it, however the membrane covering cannot carry the snow or rain load	Structure is simple and a stable one
Design of Megastructure/s	**Material**	Material is not indicated	Reinforced concrete
	Design and Dimensions of Megastructure/s (Arches, Vertical Elements, Pylon Height/Main Span Ratio)	-3 meters of pylons for 72 meters of main span -Student is aware the thickness however is not aware of specific ratios of thicknesses in respect to other elements	The main span of the arch structure is 80 meters and the pitch point is 35 meters, which is near to optimal half arch
	Design of Vertical Minor Support Elements	-There is no side span, therefore the stable cannot be well stabled -There is no foundation for anchorages	No need for minor support elements
	Design of the Covering and Cautions Against Rain-Snowloads	-A stable top membrane covering is added -However , the student is not aware of the bending behaviour of the steel and membrane covering, which can result the cover to collapse under live loading	Three meters thick solid reinforced concrete is covering the spaceship -The vault is covering the spaceship from rain and snow and good for rain water drainage
	Foundations of Megastructures	Is not indicated	Is not indicated
	Flow of Forces	Student indicates simple flow of forces in a written format	Student indicates all the flow of forces as diagrams and in a written format
	Level of Understanding	MULTISTRUCTURAL	RELATIONAL

Participant 12 – SPNotes and SPVR- Longer Span Suspension, Cable Stayed Bridge – (Multistructural to Relational)

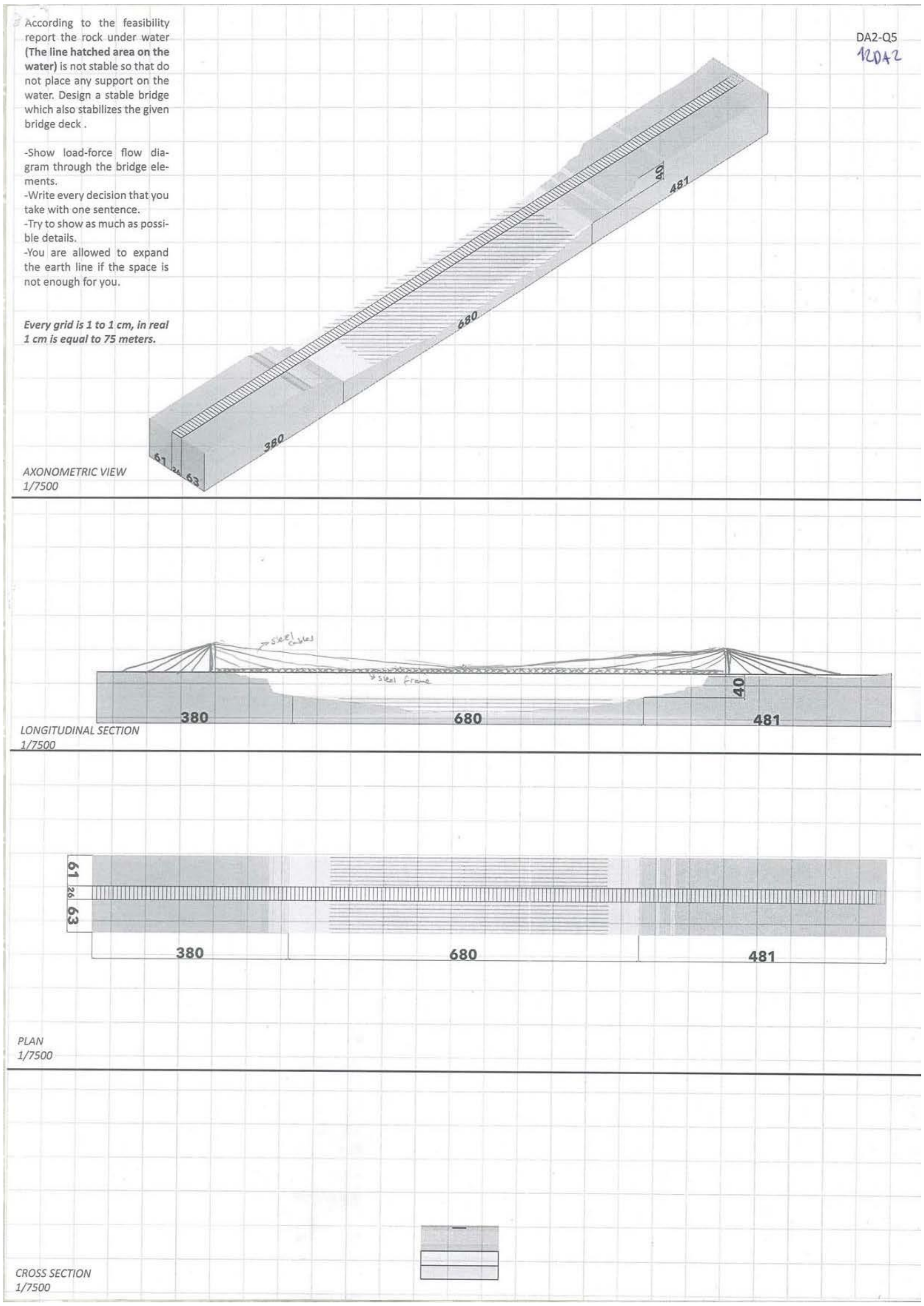

Figure 4.18. Participant 12 DA-1 Longer-Span Bridge Question

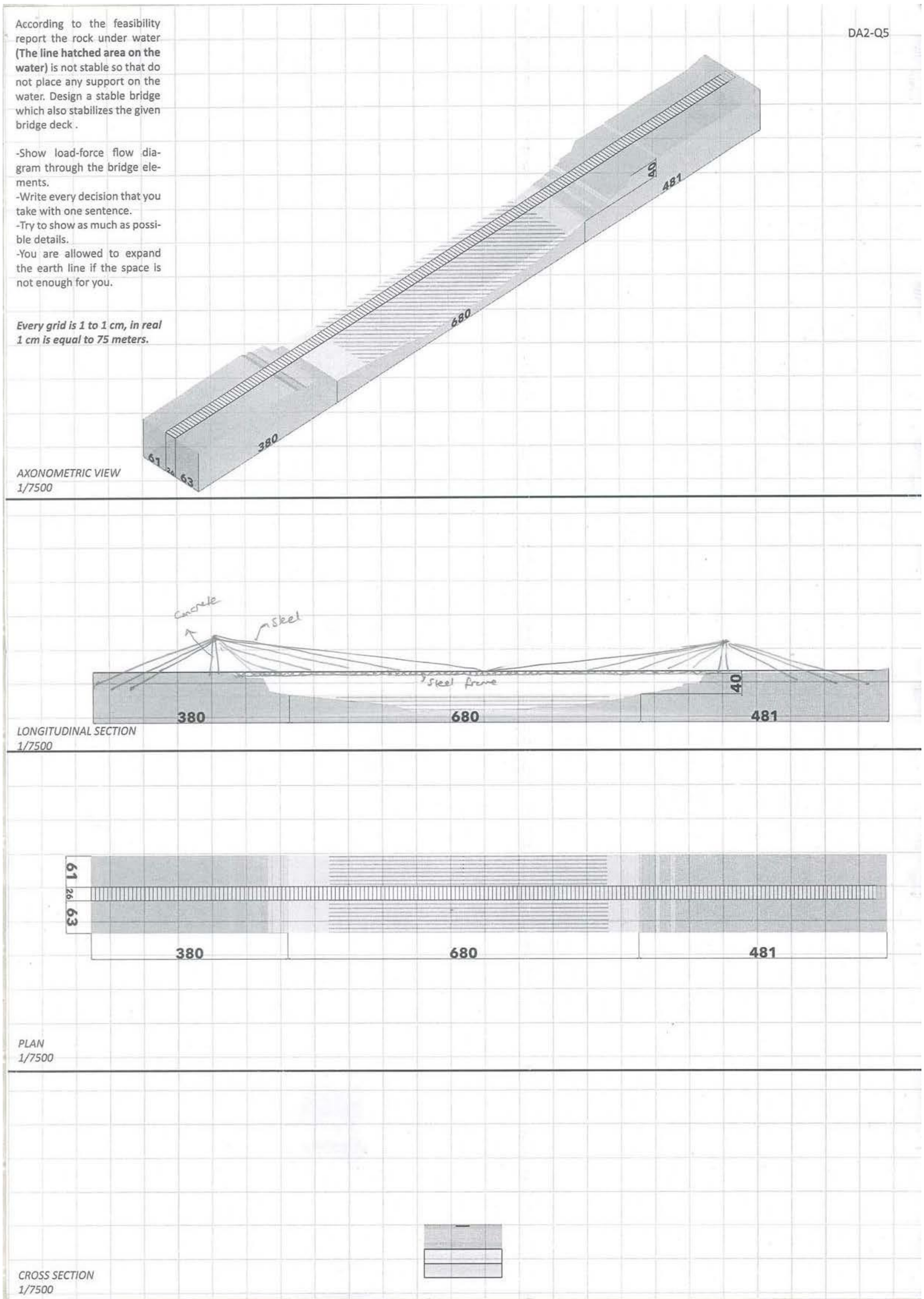

Figure 4.19. Participant 12 DA-2 Longer-Span Bridge Question

In order to compare and perceive differences between SPNotes and SPVR in terms of their utilization, another method is also developed. A student who tries SPNotes firstly and already had DA-1 and DA-2, taken into SPVR one month after. Since the participant is already familiar with the scenes from SPNotes, s/he would be able to recognize and recall the information from his first experience. During SPVR experience, the student states that combining SPNotes and SPVR is very useful in terms of reinforcing the knowledge, and the results of DA-3 confirms this situation.

In DA-1, student has designed a mono-cable cable stayed bridge composed of two pylons. The height of pylons is not enough for 1000 meters span. The deck is designed in a steel frame and the cables are meeting at the middle of the main span, which contributes to structural stability. No flow of forces is given. Due to lack of relations between structural parts the level of the student is determined as multistructural.

After experiencing SPNotes student has taken the second diagnostic assessment. However, the cable-stayed bridge design solution after DA-2 is similar to DA-1. A mono-cable cable-stayed bridge composed of two pylons insufficient in height to pass 1000 meters span is designed. Simple foundations are given and no flow of forces is indicated. Again because of the weak relations between structural parts the level of the student is determined as multistructural.

1 month after, student had SPVR experience and then taken third diagnostic assessment. There are significant improvements after DA-3 compared to first two assessments. The student has designed a double cabled suspension bridge with two “H” type pylons, which is more appropriate type of a bridge for large length of main span. Steel frames are used to support the deck; moreover, “H” type pylons are also strong against lateral loads. Steel frames are used to support the deck, which is an extensive abstract feature. Adding vertical cables between the foundations and the main cable is beneficial for the structure. The cables are meeting at the middle of the main span and the ratio of 0.5 between side to main span is contributing to structural stability. Simple foundations and flow of forces are shown as different features than

the first two assessments. Considering constructed complex relations between components and designing the parts out of the scope of the question to add structural stability, the level of the student is increased to extensive abstract.

Table 4.13. *Longer Span Suspension, Cable-Stayed Bridge Results of P-12*

	Participant Number	**P-12 1-DA2**	**P-12 2-DA2**	**P-12 3-DA2**
	Is It a Cable-Stayed or a Suspension Bridge?	A mono-cable cable stayed bridge composed of two pylons	A mono-cable cable stayed bridge composed of two pylons	A double cabled suspension bridge with two H type pylons is designed
	Is the Bridge Stable?	The height of pylons are not enough for 1km span as if in participant's solution	The height of pylons are not enough for 1km span as if in participant's solution	Beside the height of the pylons bridge is looking stable
Design of Pylon/s	**Material**	Material is not indicated	Pylons are in concrete	Steel frames are used to support the deck
Design of Pylon/s	**Dimensions of Pylons Pylon Height/Main Span Ratio**	0.1	0.1	0.07
Design of Pylon/s	**Design and Dimensions of Pylon/s**	-Vertical pylons are given -The height is not sufficient	-The pylons are getting thicker from top to bottom, 5 meters to 20 meters respectively -The height is not sufficient	-H type pylons are also strong against lateral loads -However the height is not sufficient
Design of Pylon/s	**Cautions Against Windload**	No specific application against windload	No specific application against windload	Designing hollow sectioned pylons against the wind
Design of Minor Support Elements	**Design of Minor Support Elements (Main Span)**	-The deck is designed in a steel frame, even though it is not asked -The cables are meeting at the middle of the main span	-The deck is designed in a steel frame, even though it is not asked (Extensive) -The cables are meeting at the middle of the main span	-The deck is designed in a steel frame, even though it is not asked (Extensive) -The cables are meeting at the middle of the main span
Design of Minor Support Elements	**Design of Minor Support Elements (Side Span)**	-Fan formation of multiple steel cables are composing one side span. -However foundation for anchorage is not shown	-Fan formation of multiple steel cables are composing one side span. -Foundation for anchorage is shown	-Adding vertical cables between the foundations and the main cable
Design of Minor Support Elements	**Side Span/Main Span Ratio**	0.2	0.25	0.5 The participant gives an exact ratio
	Foundations of Pylons	Is not indicated	Simple foundations are given	Simple foundations are given
	Flow of Forces	No flow of forces is given	No flow of forces is given	A simple flow of forces is given
	Level of Understanding	MULTISTRUCTURAL	MULTISTRUCTURAL	RELATIONAL

Participant 12 – Firstly SPNotes and Secondly SPVR- Arch Bridge Question – (From Unistructural to Unistructural to Extended Abstract Respectively)

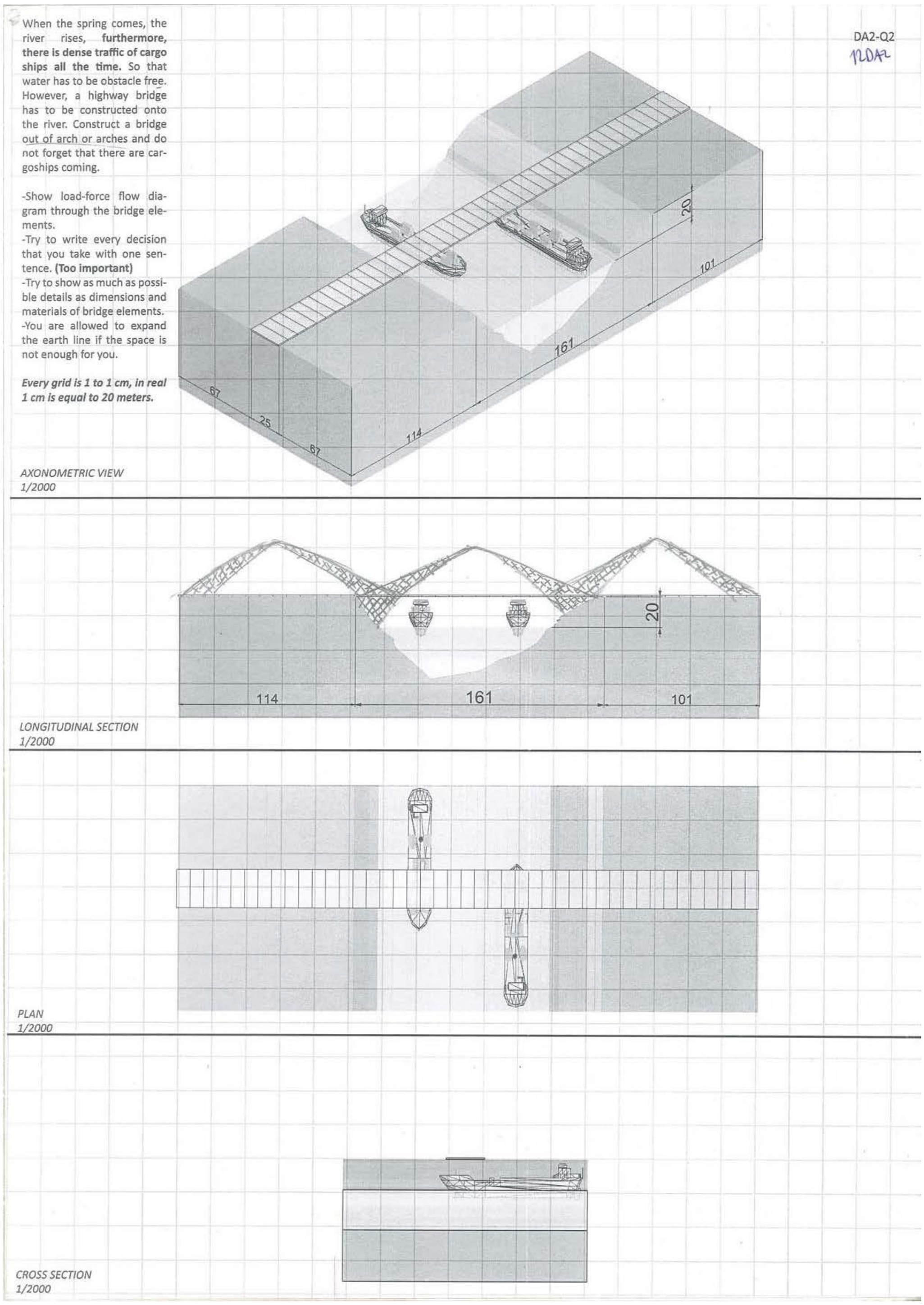

Figure 4.20. Participant 12 DA-1 Arch Bridge Question

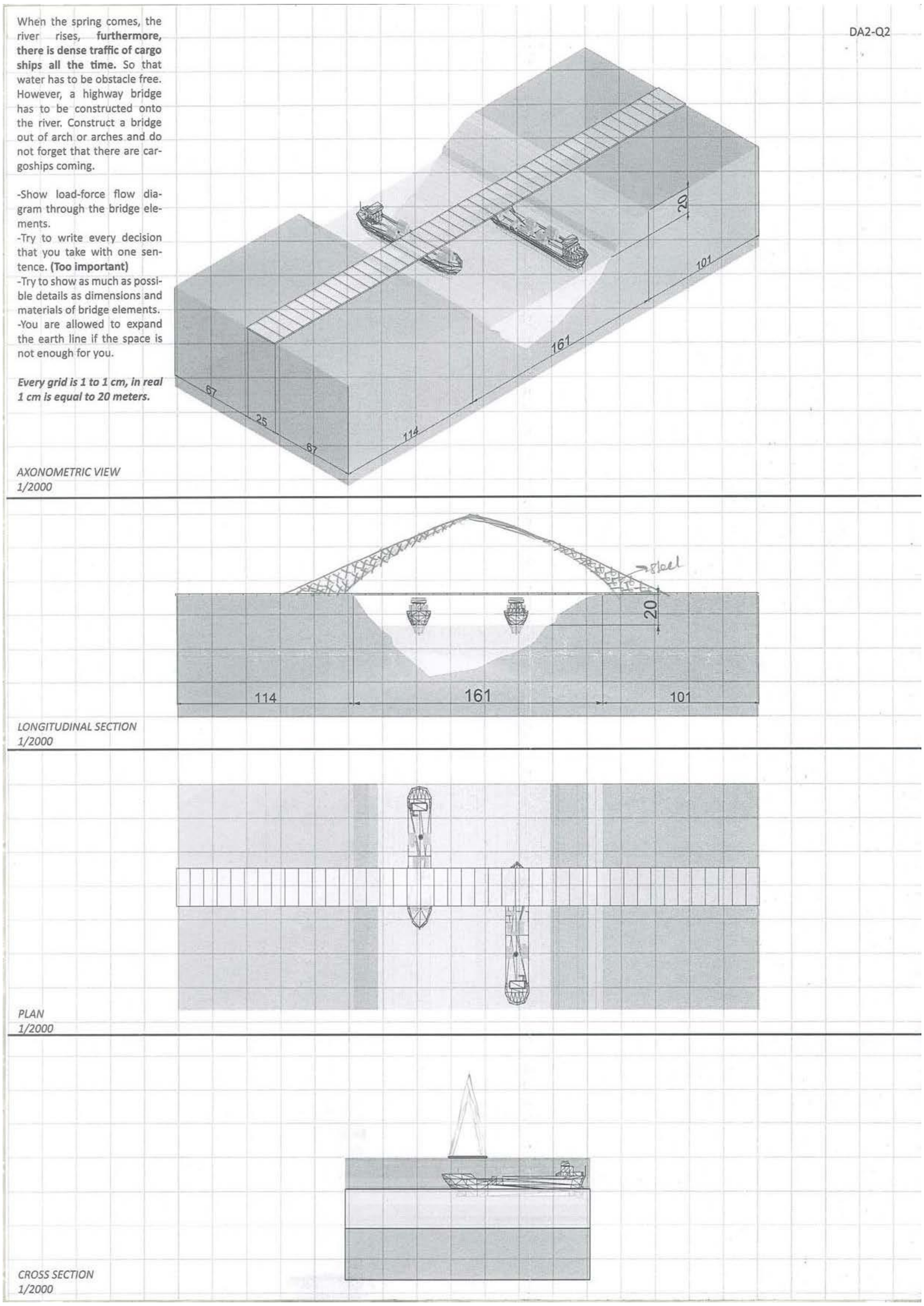

Figure 4.21. Participant 12 DA-2 Arch Bridge Question After Having SPNotes

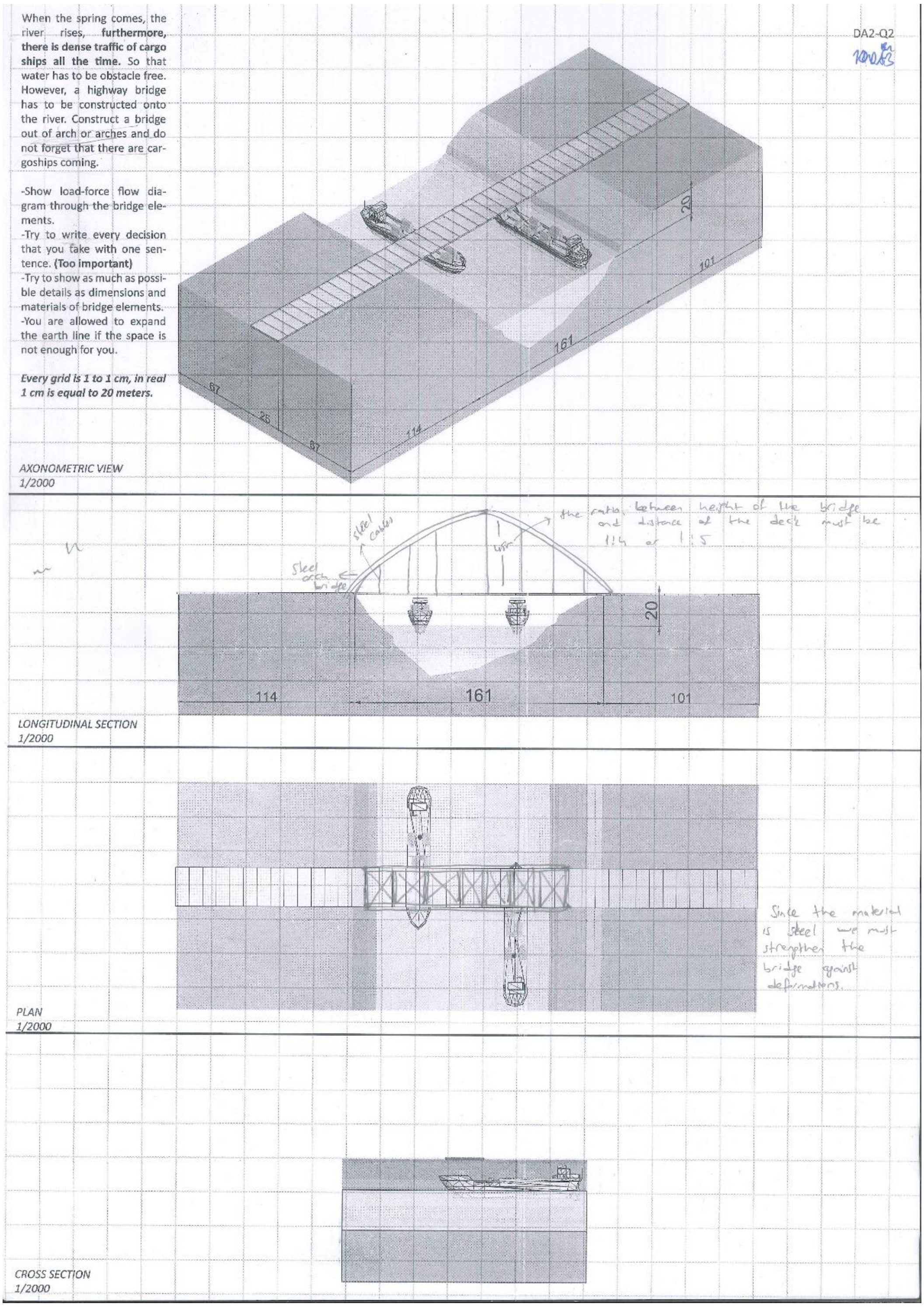

Figure 4.22. Participant 12 DA-3 Arch Bridge Question after Having SPVR

In order to compare and perceive differences between SPNotes and SPVR in terms of their utilization, another method is also developed. A student who tries SPNotes firstly and already had DA-1 and DA-2, taken into SPVR after one month. Since the participant is already familiar with the scenes from SPNotes, s/he would be able to recognize and recall the information from his first experience. During the SPVR experience, the participant designed a through triple arch bridge, however the thickness of the bridge is not indicated.

Moreover, side arches are not necessary for structural stability, the cross section on the top is 1 meter and 20 meters while going through foundations. However, the since the pitch of the arch is 1 meters, it is not enough to have a stable bridge

After experiencing SPNotes student has taken the second diagnostic assessment. The participant designed a through double arch bridge, however the thickness of the bridge is not indicated. Moreover, any steel cables added to stabilize the bridge, so the deck is exposed to any vertical loads.

1 month after, student had SPVR experience and then taken third diagnostic assessment. There are significant improvements after DA-3 compared to first two assessment. A steel double arch bridge with cross bracings between arches is designed. Moreover, the participant shows the hinge between half arches and integrated the bridge with 3 meters thick steel arches for 161 meters of main span. Student consciously gives the height of the arches and steel cross braces are shown between the arches against the lateral loads that the student indicated in a written format as well.

Table 4.14. *Arch Bridge Question Results of P-12*

	Participant Number	P-12 1-DA2	P-12 2-DA2	P-12 3-DA2
	Is it an arch bridge?	The participant designed a through triple arch bridge, however the thickness of the bridge is not indicated. Moreover, any steel cables added to stabilize the bridge, so the deck is exposed to any vertical loads	The participant designed a through double arch bridge, however the thickness of the bridge is not indicates. Moreover, any steel cables added to stabilize the bridge, so the deck is exposed to any vertical loads	A steel double arch bridge with cross bracings between arches is designed
	Is the Bridge Stable?	(-)	(-)	(++)
Design of Arch/es	**Material**	Material is not indicated	The bridge is designed out of steel	The bridge is designed out of steel
	Elaboration on Arch Section Dimensions of Arches Using Minor Support Elements	Three arches with cross bracings The side arches are not necessary for structural stability The cross section on the top is 1 meters and 20 meters while going through foundations -However the since the pitch of the arch is 1 meters, it is not enough to have a stable bridge	An arch with space-framelike cross bracings The cross section on the top is 1 meters and 20 meters while going through foundations -However the since the pitch of the arch is 1 meters, it is not enough to have a stable bridge	-The participant shows the hinge between half arches -3 meters thick steel arches for 161 meters of main span
	Height/Main Span Ratio	0.41	0.225	Student consciously gives the height of the arches
Design of Minor	**Design of Minor Support Elements (Steel Cables, Trusses etc.)**	Steel cables are not present, therefore the structure is not stable	Steel cables are not present, therefore the structure is not stable	Vertical steel cables are present between the deck and the arches
	Middle Supports Between Arches (Against Horizontal Loads)	Did not indicate the plan of the bridge	Two arches are leaning on each other to stabilize each other	Steel cross braces are shown between the arches against the lateral loads that the student indicated in a written format as well
	Foundations	Is not indicated	Is not indicated	Is not indicated
	Flow of Forces	Did not indicate	Did not indicate	A simple flow of forces is given
Level of Understanding		UNISTRUCTURAL	UNISTRUCTURAL	EXTENDED ABSTRACT

Participant 14 – SPVR- Longer Span Suspension, Cable Stayed Bridge – (Multistructural to Relational)

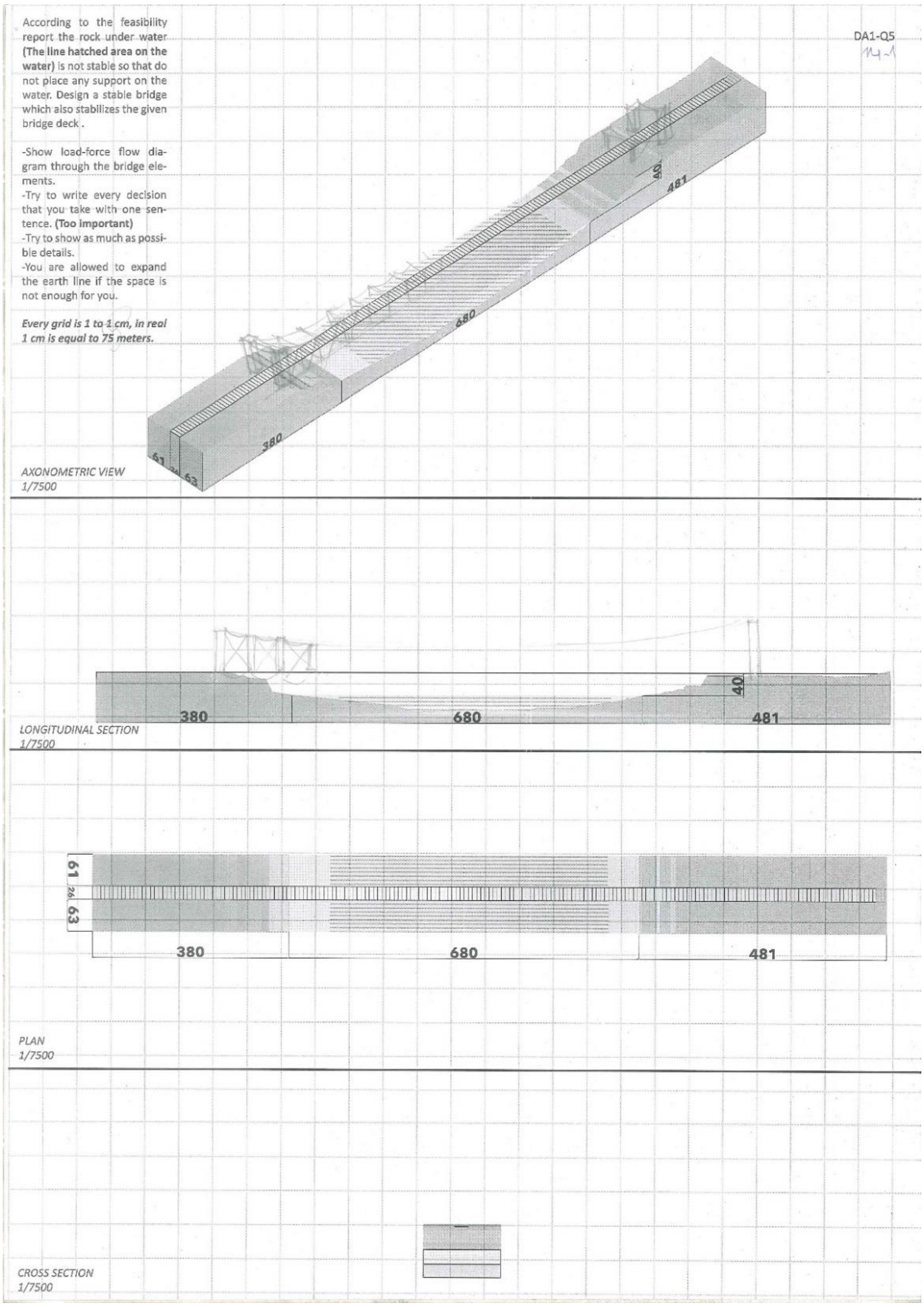

Figure 4.23. Participant 14 DA-1 Longer-Span Bridge Question

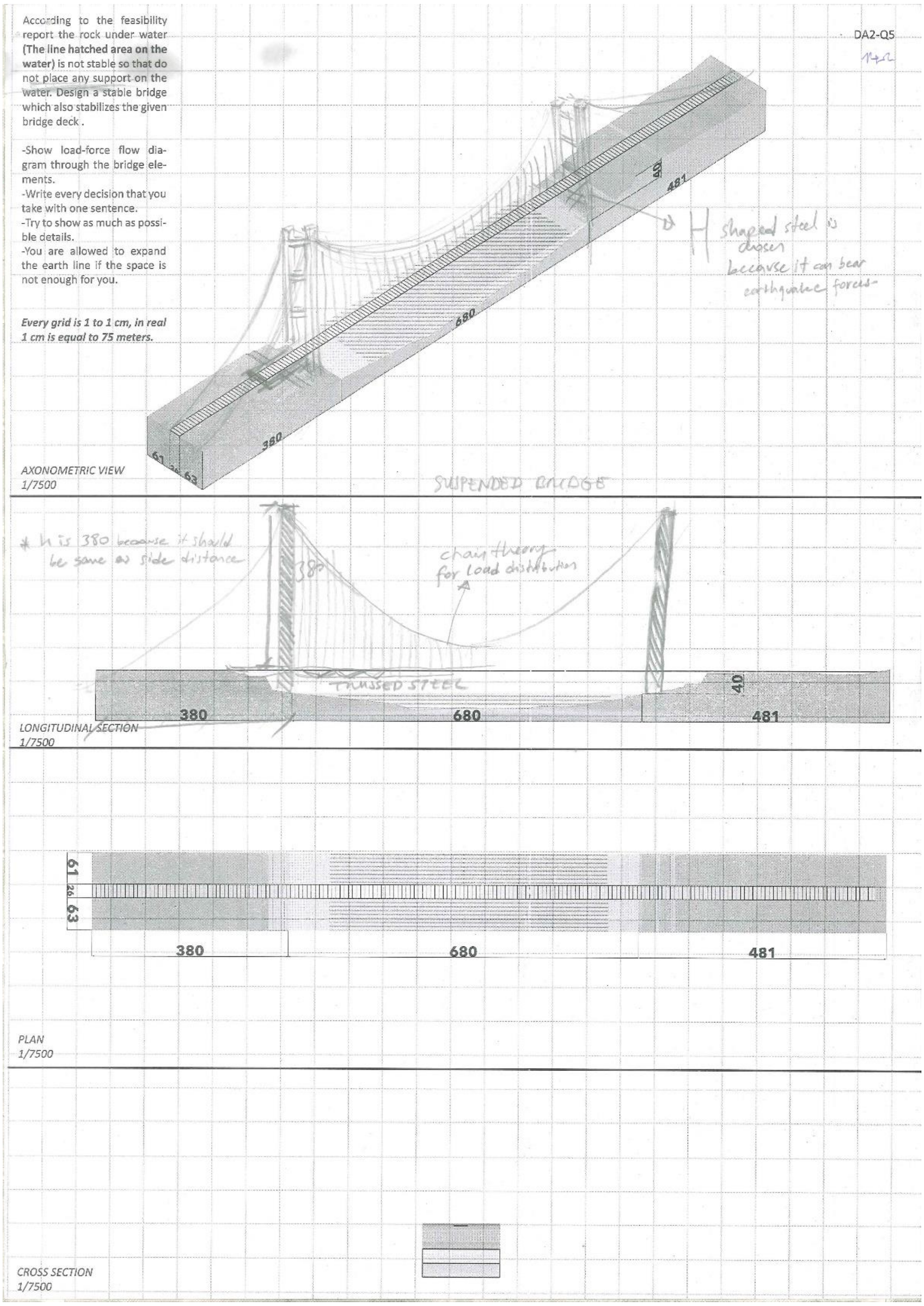

Figure 4.24. Participant 14 DA-2 Longer-Span Bridge Question

Through the end of the research after finishing testing bachelor students, the discussion to apply SPVR to graduate students is put forward. So that, two graduate students thirteenth and fourteenth participant is invited to experiment as outliers. Although the bridges obtained after first diagnostic assessment are in the similar level with bachelor students' solutions; in the end of that part it is proved that SPVR is also beneficial to graduate students. Furthermore, since graduate students are experienced in architectural offices and detailing; rather than a concept bridge design, highly robust bridge designs were obtained.

In DA-1, the participant has designed a steel double arched bridge without bracings between the arches. The steel bridge is looking partially stable because it lacks bracings against lateral loads. A detail between steel and cable connection is given, yet the thicknesses of arches are indicated as lines. Although a buried foundation is not indicated, the student is aware of distributing loads through the legs of the bridge. A simple flow of forces is given. Since the participant is able to recognize and design structural parts but having weak relations between them makes the level of the student as multistructural.

In contrast to DA-1, after having SPVR education the long-span bridge design presented in DA-2 has significantly improved. The designed bridge is a steel double arch bridge with horizontal bracings between the arches. Arches are getting thinner through the top and vertical steel studs, steel cables are added. The thickness of the steel arch is 10 meters on the bottom, in addition to that arch beams are made out of trussed steel against compression and tension forces as an extended abstract feature. The participant is aware of the fact that the height/span ratio is an important feature. On the contrary to DA-1 horizontal concrete bracings are indicated, in addition to that participant explained the reason behind using that particular type of bracing. A very detailed buried foundation out of concrete and flow of forces indicating compression-tension state is indicated. All of these reasons are sufficient to increase level of the student from multistructural to extended abstract.

Table 4.15. *Longer Span Suspension, Cable-Stayed Bridge Results of P-14*

	Participant Number	P-14 1-DA1	P-14 2-DA2
	Is It a Cable-Stayed or a Suspension Bridge?	Double cable suspension bridge out of two H type pylons	Double cable suspension bridge out of two H type pylons
	Is the Bridge Stable?	The bridge is not stable because there is no side span to balance the forces	The bridge is a very stable one
Design of Pylon/s	**Material**	No material is indicated	Bridge is designed out of steel
Design of Pylon/s	**Dimensions of Pylons Pylon Height/Main Span Ratio**	0.09	0.5
Design of Pylon/s	**Design and Dimensions of Pylon/s**	-However, the thickness and the height is not enough	-H type 30 meters thick steel pylons are designed against the windload -Adding more bracings between studs of the pylons
Design of Pylon/s	**Cautions Against Windload**	Hollow pylons admit wind to pass	Hollow pylons admit wind to pass
Design of Minor Support Elements	**Design of Minor Support Elements (Main Span)**	Modular crossed steel cable bracings are designed through the deck	-Trussed steel deck and the detail of it is indicated -Catenary arch formula is indicated to formulize the main cable
Design of Minor Support Elements	**Design of Minor Support Elements (Side Span)**	There is no side span	Foundations and the cables are composing the side span
Design of Minor Support Elements	**Side Span/Main Span Ratio**	There is no side span	0.5 The participant is aware of the ratio
	Foundations of Pylons	No foundation is indicated	No foundation is indicated, however the participant is aware of flow of forces
	Flow of Forces	No flow of forces is given	A simple flow of forces is given
	Level of Understanding	UNISTRUCTURAL	EXTENDED ABSTRACT

4.4. StructurePuzzle Questionnaire

Since impact of motivation on learning has major significance as one of the elements of game-based learning; the participants were asked to complete a questionnaire to understand their personal ideas about the training practice they have entered. This Likert-Scale type questionnaire is a five-point scale which is used to allow the individual to express how much they agree or disagree with a particular statement. The questions are related to individual enjoyment that they have and immersive elements as 3D visualization, haptics, colors, spatial sound effects and narrative in the scenes in SPVR or SPNotes. Moreover, at the last part, their recommendations about the game are asked; so that these can be used as features that can make the better educational game.

Below the examples and comparison of SPVR Questionnaire and SPNotes Questionnaire can be seen. The overall grading is done by calculating the arithmetic mean of the grades given by the students to each question.

StructurePuzzleVR Questionnaire

1- I had fun with StructurePuzzleVR.

Not at all [1] [2] [3] [4] [5] Definitely

2- Now I am more informed about the dimensions (span sizes, section thicknesses, ratios) of long-span bridges than before the StructurePuzzle.

Not at all [1] [2] [3] [4] [5] Definitely

2A- Now I am more informed about the materials of long-span bridges than before the StructurePuzzle.

Not at all [1] [2] [3] [4] [5] Definitely

3- Now I am more informed about the behaviour of various types of structures under loading, under wind force and how they react to them.

Not at all [1] [2] [3] [4] [5] Definitely

4- Being able to touch and experience the structures in one to one scale helped me to keep my concentration through the game.

Not at all [1] [2] [3] [4] [5] Definitely

5- The specialized contexts through (such as Ancient Rome in aqueduct scene, construction site in arch bridge scene) the scenes keep my concentration through the game.

Not at all [1] [2] [3] [4] [5] Definitely

4- Being able to touch and experience the structures in one to one scale helped me to understand the real-life scale of the structures better.

Not at all [1] [2] [3] [4] [5] Definitely

4A- Now I am better at visualizing the real life dimensions of the structures in my mind. (For example 1.2 kilometers in real life)

Not at all [1] [2] [3] [4] [5] Definitely

6- The various colourful worlds in the game help me to keep my concentration.

Not at all [1] [2] [3] [4] [5] Definitely

7- The contextualized sound effects (birds in the wood, construction sound in construction area, wind sound, sound of steel and concrete) helped me to keep my concentration through the game.

Not at all [1] [2] [3] [4] [5] Definitely

8- If this system is applied at least for the specific parts of the other courses as well, I believe that I could learn and internalize the information more than the classical way of teaching.

Not at all [1] [2] [3] [4] [5] Definitely

If you have any other recommendations or thoughts please write in 1-2 sentences.

(These recommendations can be related to classical way of teaching through notes other than StructurePuzzleVR)

Figure 4.25. StructurePuzzleVR Questionnaire

StructurePuzzleNotes Questionnaire

1- I had fun with StructurePuzzleNotes.

Not at all [1] [2] [3] [4] [5] Definitely

2- Now I am more informed about the dimensions (span sizes, section thicknesses, ratios) of long-span bridges than before the StructurePuzzle.

Not at all [1] [2] [3] [4] [5] Definitely

2A- Now I am more informed about the materials of long-span bridges than before the StructurePuzzle.

Not at all [1] [2] [3] [4] [5] Definitely

3- Now I am more informed about the behaviour of various types of structures under loading, under wind force and how they react to them.

Not at all [1] [2] [3] [4] [5] Definitely

4- Being able to see the behaviour of the structures in notes helped me to keep my concentration through the notes.

Not at all [1] [2] [3] [4] [5] Definitely

5- The specialized contexts through (such as Ancient Rome in aqueduct scene, construction site in arch bridge scene) the scenes keep my concentration through the notes.

Not at all [1] [2] [3] [4] [5] Definitely

4- Now I understand the real-life scale of the structures better.

Not at all [1] [2] [3] [4] [5] Definitely

4A- Now I am better at visualizing the real life dimensions of the structures in my mind. (For example 1.2 kilometers in real life)

Not at all [1] [2] [3] [4] [5] Definitely

6- The various colourful worlds in the notes help me to keep my concentration.

Not at all [1] [2] [3] [4] [5] Definitely

7- After a while I had hard time to keep my concentration at a certain level.

Not at all [1] [2] [3] [4] [5] Definitely

If you have any other recommendations or thoughts please write in 1-2 sentences.

(These recommendations can be related to classical way of teaching through notes other than StructurePuzzleVR)

Figure 4.26. StructurePuzzleNotes Questionnaire

Table 4.16. *SPVR and SPNotes Questionnaires Comparison-Undergraduates*

Questions	SPVR	SPNotes
I had fun with SPVR/SPNotes	4.8	3.6
Now I am more informed about the dimensions (span sizes, section thicknesses, ratios) of long-span bridges than before the StructurePuzzle.	5.0	4.0
Now I am more informed about the materials of long-span bridges than before the StructurePuzzle.	5.0	4.0
Now I am more informed about the behavior of various types of structures under loading, under wind force and how they react to them.	5.0	3.4
SPVR Question: Being able to touch and experience the structures in one to one scale helped me to keep my concentration through the game. **SPNotes Question:** Being able to see behavior of the structures help me to keep my concentration through the notes.	4.8	3.4
The specialized contexts through (such as Ancient Rome in aqueduct scene, construction site in arch bridge scene) the scenes keep my concentration through the SPVR/SPNotes	4.5	3.8
SPVR Question: Being able to touch and experience the structures in one to one scale helped me to understand the real-life scale of the structures better. **SPNotes Question:** Now I understand the real-life scale of the structures better.	5.0	3.8
Now I am better at visualizing the real-life dimensions of the structures in my mind.	4.8	3.0
The various colorful worlds in the game help me to keep my concentration.	4.3	3.6
Question only for SPVR: The contextualized sound effects (birds in the wood, construction sound in construction area, wind sound, sound of steel and concrete) helped me to keep my concentration through the game.	3.8	(NA)
Question only for SPVR: If this system is applied at least for the specific parts of the other courses as well, I believe that I could learn and internalize the information more than the classical way of teaching.	5.0	(NA)
Question only for SPNotes: After a while I had hard time to keep my concentration at a certain level.	(NA)	3.6

4.5. Feedback and Drawbacks

Couple of feedback are given by the students regarding the SPVR or issues with VR headset generally. All the written feedback given by the students who had SPVR can be used for improving the game as a future study. These are:

- *"If I could play SPVR with my friend and build structures together, I would have more fun than I already have."*
- *"VR is hurting my nose because of my glasses."*
- *"SPVR is beneficial to remember the knowledge of construction details. It is good for architecture students as well as civil engineering students."*

Moreover, author's general observation on disadvantages of SPVR and the headset are given. Firstly, it is generally tiring to wear VR headset for 45 minutes because of its weight, short-term mild eye redness and mild nausea for some of the participants, however, if the student enjoys the game it is not a problem for him/her. Secondly, the problems of SPVR are that, even though SPVR has given quite successful results at the end of the experiment; the preparation of the game was took a long-time and it is required to learn a new game engine software for the author. However, if design process of the game is supported by someone who specializes in C# programming language, which is the developer language of Unity 3D, SPVR could have been more interactive virtual reality game.

CHAPTER 5

CONCLUSION

This research initiated with the intention of contributing of how game based immersive virtual reality technologies can be utilized to improve novice architecture students' intuitive understanding of behaviors of structures. The main purpose of this study is to make contribution to literature on the conception of immersive virtual reality learning environment and its relationship with structural design education through constructivist learning. In the end, an IVR application, StructurePuzzleVR is designed to investigate potentials and the role of IVR application related to its methodological integration as a learning medium for learning how to design and develop an insight about basic notion related to structure design.

According to researched literature, there is no IVLE game-based education methodology is designed before for the specified intention. Therefore, starting with the literature review, the study is elaborated on complementary analysis of educational objectives, unique features supported by VR technology and learning theories. Moreover, to test the hypothesis and have more clarified results, the subject of "learning behaviours of structures" narrowed down to "learning behaviours of long-span bridge structure".

Beginning with the Constructivist Learning Theory and Problem-Based Learning the VR application is designed as a learning environment. Furthermore, the distinguishing features of VR compared to traditional education based on notes, such as immersive visualization, haptics, stereo audio, physics are integrated into the application. In this way a meaningful learning experience of solving a design problem is aimed. Thus, StructurePuzzleVR which appeal to participants' visual, tactile, hearing sensations by interacting with the participants' as much as possible is to create more memorable and meaningful learning experience.

SPVR involves twelve different interactive scenarios related to basic working principles of beam, arch, cable-stayed and suspension bridges. Moreover, a control group which is an application lacks of distinguishing specialties of VR is required in order to understand possible contributions and the benefits of SPVR. Therefore, StructurePuzzleNotes is designed by converting the scenes involved in SPVR to lecture notes from 16 colorful pages. In total 12 novice second year architecture students are participated in the experiment, besides that, 2 more graduate architecture students also participated as outliers.

The experiment is installed as three parts accordingly, first is diagnostic assessment 1 (DA-1) to detect priori knowledge of students by asking them four open-ended questions to design arch, cable-stayed, suspension long-span bridges, and a long-span covering question out of their comfort zone. Second is education or learning part in which one group is taking into SPVR while other in SPNotes for 45 minutes each. And finally, second diagnostic assessment (DA-2) that is composed of the same or slightly different questions directed in DA-1, so that data is collected to understand contribution and comparison of SPVR and SPNotes.

A crucial part of the research for meaningful utilisation is to find a tangible way of measuring the impact of IVLE. Hence, after the experiment the results of DA-1 and DA-2 are analyzed according to Structure of the Observed Learning Outcome (SOLO) Taxonomy which is a better option while classifying participants' solutions according to their complexity related with quality. Basic parameters of the long-span bridge design such as dimensions, usage of material, innovative solutions, flow of forces are identified and participants' answers are categorized to apply on SOLO Taxonomy. Each individual performance on different categories are identified to structured levels of complexity in education based on the rubric derived from the SOLO taxonomy to see different degrees of advancements. Besides, after DA-2, a questionnaire in the format of 1-5 Likert scale is given to participants to understand how they feel about what they have learnt and whether they are enjoyed or not about SPVR or SPNotes.

Through the experiment process, couple of drawbacks are noted on a few participants due to VR headset such as, short-term mild nausea and eye redness.

According to the results, in the end almost all of the bachelor and graduate students have designed more complex long-span bridges. However, although the designs of all the participants are in approximately on the same level at the beginning in DA-1; the majority of the students taken into SPVR have designed far more complex and suitable structures according to questions in DA-2. Moreover, although the priori knowledge of two graduate students are approximately on the same level as the bachelor students, after having SPVR education they are able to fuse their professional knowledge with the knowledge coming from the IVLE, even though this information is not taught in SPVR. Useful results can be achieved if the StructurePuzzleVR is integrated with the professional life as well as in school education. According to StructurePuzzle Questionnaire and the observations of the author, majority of the participants educated in SPVR motivated, enjoyed and found the SPVR more informative, other than that, some of them indicated that it can be used in structure courses or can be designed for multiplayer use. However, although some of them liked the SPNotes, they indicated that the experience is dull time to time. One participant who experienced first SPNotes and after that SPVR indicated that, s/he found SPVR more enjoyable and informative.

An overview of findings submits that, an IVLE providing such immersive features are able to provide tangible and meaningful experience on learning structural behaviours and designing structures. Therefore, the results of the study confirm the initial hypothesis of this study and it’s impact on learning at this point are encouraging for future research.

Future Studies

According to feedback and drawbacks, the SPVR game is tried to be developed more in terms of interactivity and immersivity by targeting more faculties.

SPVR can be redesigned for multiplayer purposes and allows participants to build their structures more freely after learning the basics of these structures. Moreover, it is observed that, SPVR is has great potentials in teaching other architecture education related subjects other than long-span structure education. Therefore, these potentials should be investigated deeply and new immersive virtual reality learning environments can be designed. As a last, although the study firstly targeted undergraduate students, the fact that it is also beneficial for graduate architecture students made the author to think about adapting SPVR for architects and civil engineers. This shows the great capability of flexibility and adaptation of virtual reality games as an interactive learning medium.

Eventually, interactive IVLEs has great potentials in architectural education as well as other professions. Hence, these potentials supported by feedback should deeply be analyzed and new IVLEs should be developed.

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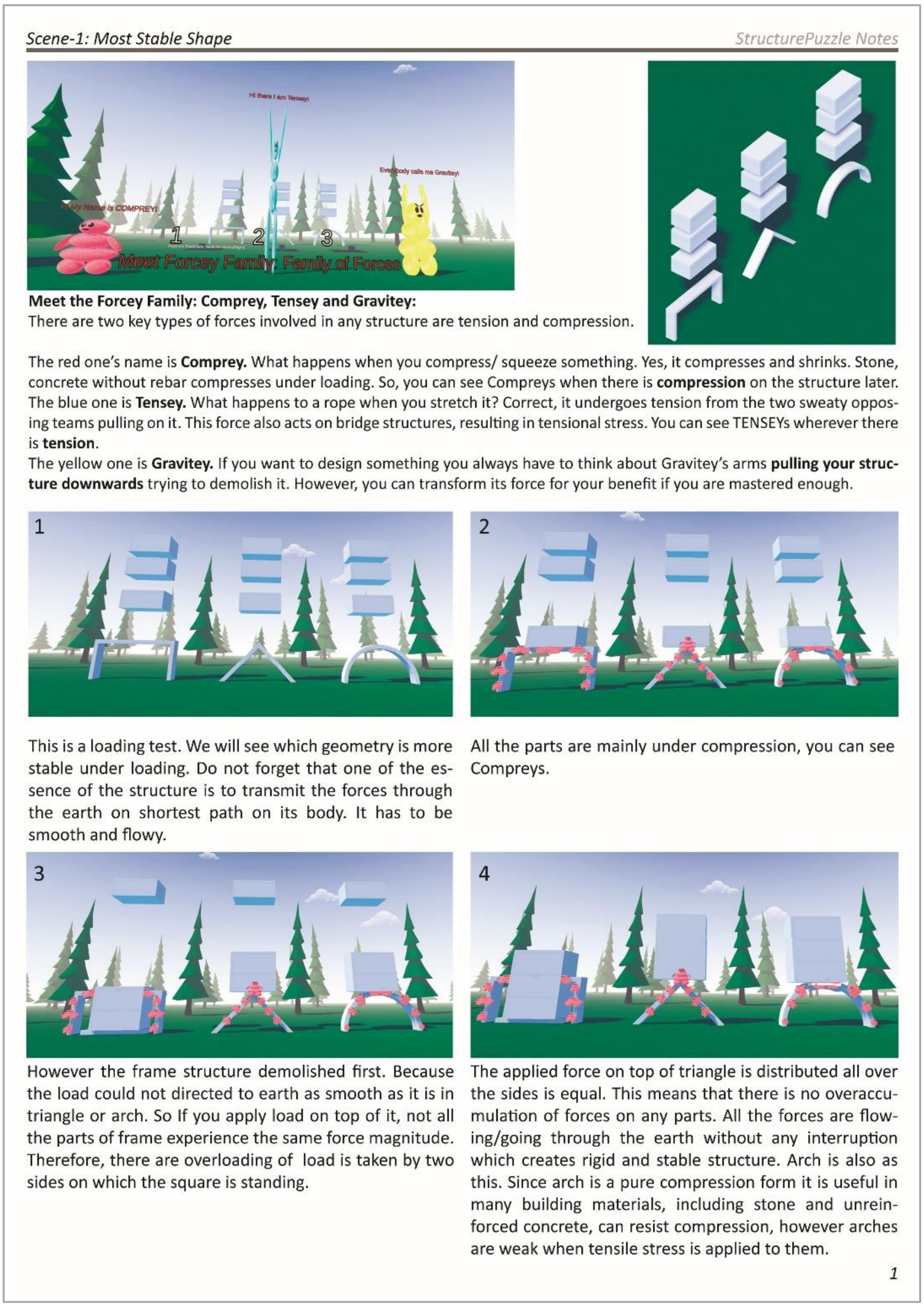
APPENDICES

A. STRUCTUREPUZZLENOTES



Scene-1: Most Stable Shape — *StructurePuzzle Notes*

Meet the Forcey Family: Comprey, Tensey and Gravitey:
There are two key types of forces involved in any structure are tension and compression.

The red one's name is **Comprey.** What happens when you compress/ squeeze something. Yes, it compresses and shrinks. Stone, concrete without rebar compresses under loading. So, you can see Compreys when there is **compression** on the structure later.
The blue one is **Tensey.** What happens to a rope when you stretch it? Correct, it undergoes tension from the two sweaty opposing teams pulling on it. This force also acts on bridge structures, resulting in tensional stress. You can see TENSEYs wherever there is **tension**.
The yellow one is **Gravitey.** If you want to design something you always have to think about Gravitey's arms **pulling your structure downwards** trying to demolish it. However, you can transform its force for your benefit if you are mastered enough.

1

This is a loading test. We will see which geometry is more stable under loading. Do not forget that one of the essence of the structure is to transmit the forces through the earth on shortest path on its body. It has to be smooth and flowy.

2

All the parts are mainly under compression, you can see Compreys.

3

However the frame structure demolished first. Because the load could not directed to earth as smooth as it is in triangle or arch. So If you apply load on top of it, not all the parts of frame experience the same force magnitude. Therefore, there are overloading of load is taken by two sides on which the square is standing.

4

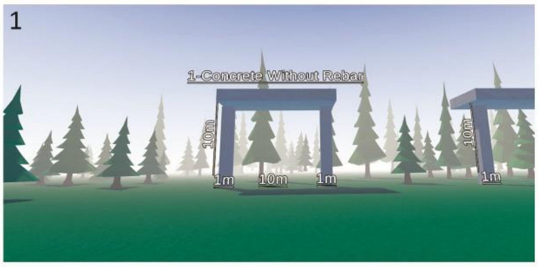
The applied force on top of triangle is distributed all over the sides is equal. This means that there is no overaccumulation of forces on any parts. All the forces are flowing/going through the earth without any interruption which creates rigid and stable structure. Arch is also as this. Since arch is a pure compression form it is useful in many building materials, including stone and unreinforced concrete, can resist compression, however arches are weak when tensile stress is applied to them.

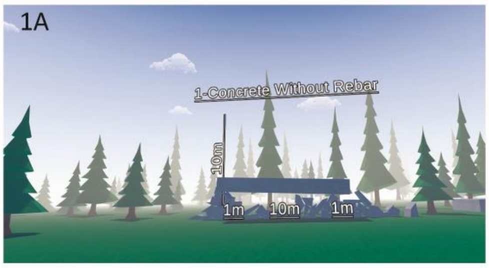
1

Figure A.1. Most Stable Shape

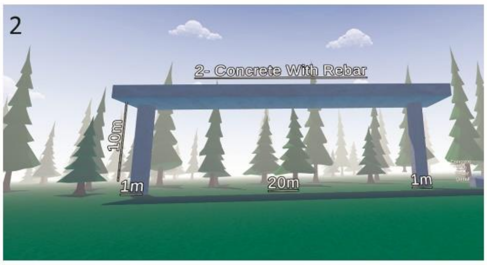
Scene-2: Buckling and Fraction StructurePuzzle Notes

In this scene, you will learn the general ratio between span dimensions and section thicknesses of reinforced concrete and steel columns in a frame structure.

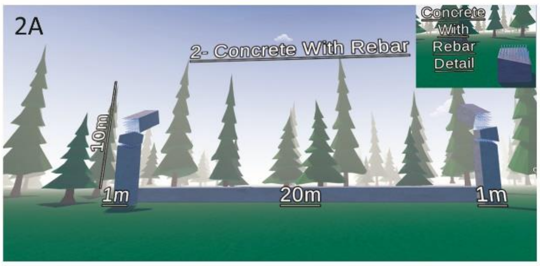




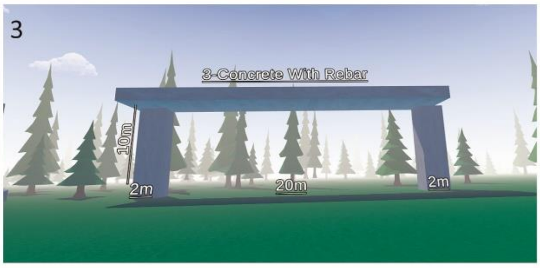
Without rebars (steel bars) in concrete, it is just dust and ashes under loading. It stays only under compression and it could be devastated as this.

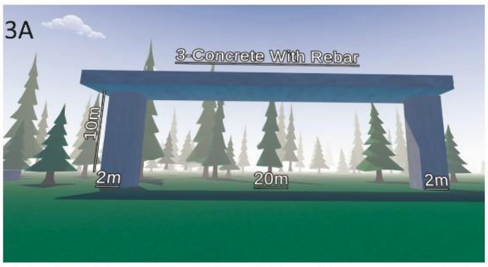


Concrete is very strong in compression, but not strong in tension. This is why we add reinforcing steel for tensioning it a little against loading. This strengthens the concrete in tension and in shear.



However, the ratio between section thickness of the reinforced concrete columns and span is 1m/20m=1/20. Generally this would be at least 1/10 in reinforced concrete. Therefore the structure is not stable under loading.



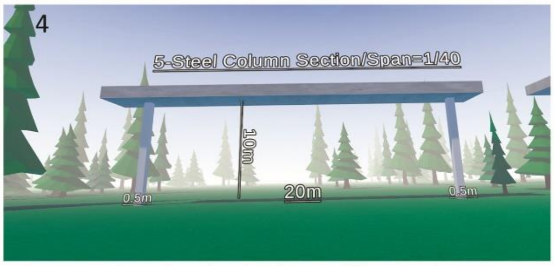


This time the structure is reinforced concrete and the ratio between section thickness of the reinforced concrete columns and span is 1m/10m=1/10. So it is stable under loading. (as per ACI 318-14)

2

Figure A.2. Buckling and Fraction

Scene-2: Buckling and Fraction *StructurePuzzle Notes*

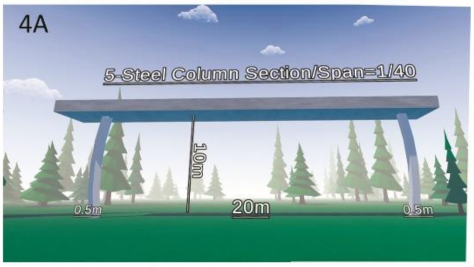


Behaviour of steel under loading is different than concrete and the reinforced concrete.

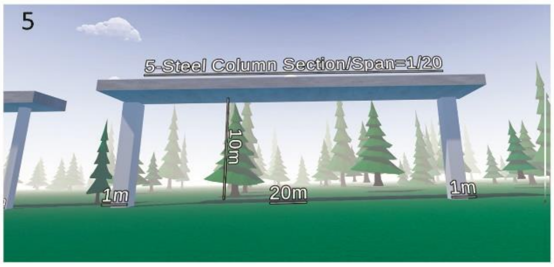
-Steel has high tensile strength and concrete has high compressive strength.

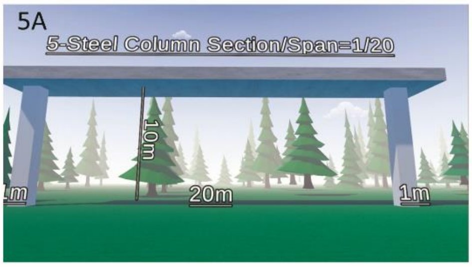
-In steel structure, span to section ratio is 1/20. So it has more loading capacity than the RC concrete.

-Steel framed structure is more resistant to earthquake and wind because it is more elastic.

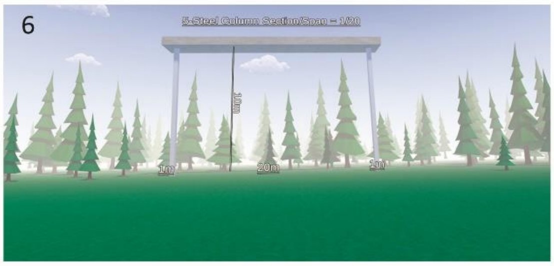


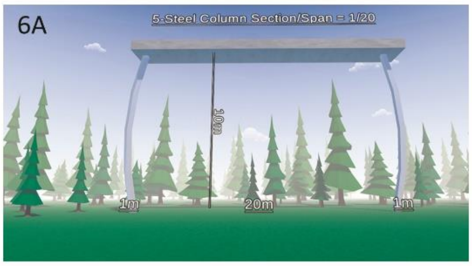
In this scene, the span to cross section ratio is 0.5/20=40. So the steel columns are bent.





However in this, the span to cross section ratio is 1/20=20. So the structure stays stable.





Although in this scene, the span to cross section ratio is 1/20=20, the structure could not stand stable because the height of columns are too much to bear the load. So it buckles as is you are pressing on top of one stick pasta. What could happen if you were doing this on RC concrete?

https://gharpedia.com/difference-between-reinforced-concrete-and-steel-framed-structure/

3

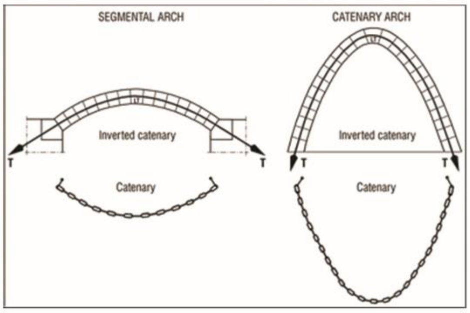
Figure A.3. Buckling and Fraction

Scene-3 Catenary Arch- Shapened by the Gravity

StructurePuzzle Notes

Catenary arch shape is created by pulling two sides of chain and releasing them. So the whole structure is shapened by gravity and if a shape is shapened by gravity if you turn it upside down it can also works against gravity as well.

The 17th-century scientist Robert Hooke wrote, *“As hangs a flexible cable so, inverted, stand the touching pieces of an arch."*



What makes the catenary arch important is its ability to withstand weight. For an arch of uniform density and thickness, supporting only its own weight, every part of catenary is in perfect equilibrium that makes the catenary is the **ideal curve.**

Catenary arch structure of Taq Kasra. AD. 540

Figure 10 (a) Chain model and (b) the constructed cathedral of Gaudi's Sagrada Familia (Source photo 10 (b): Wikipedia commons file)

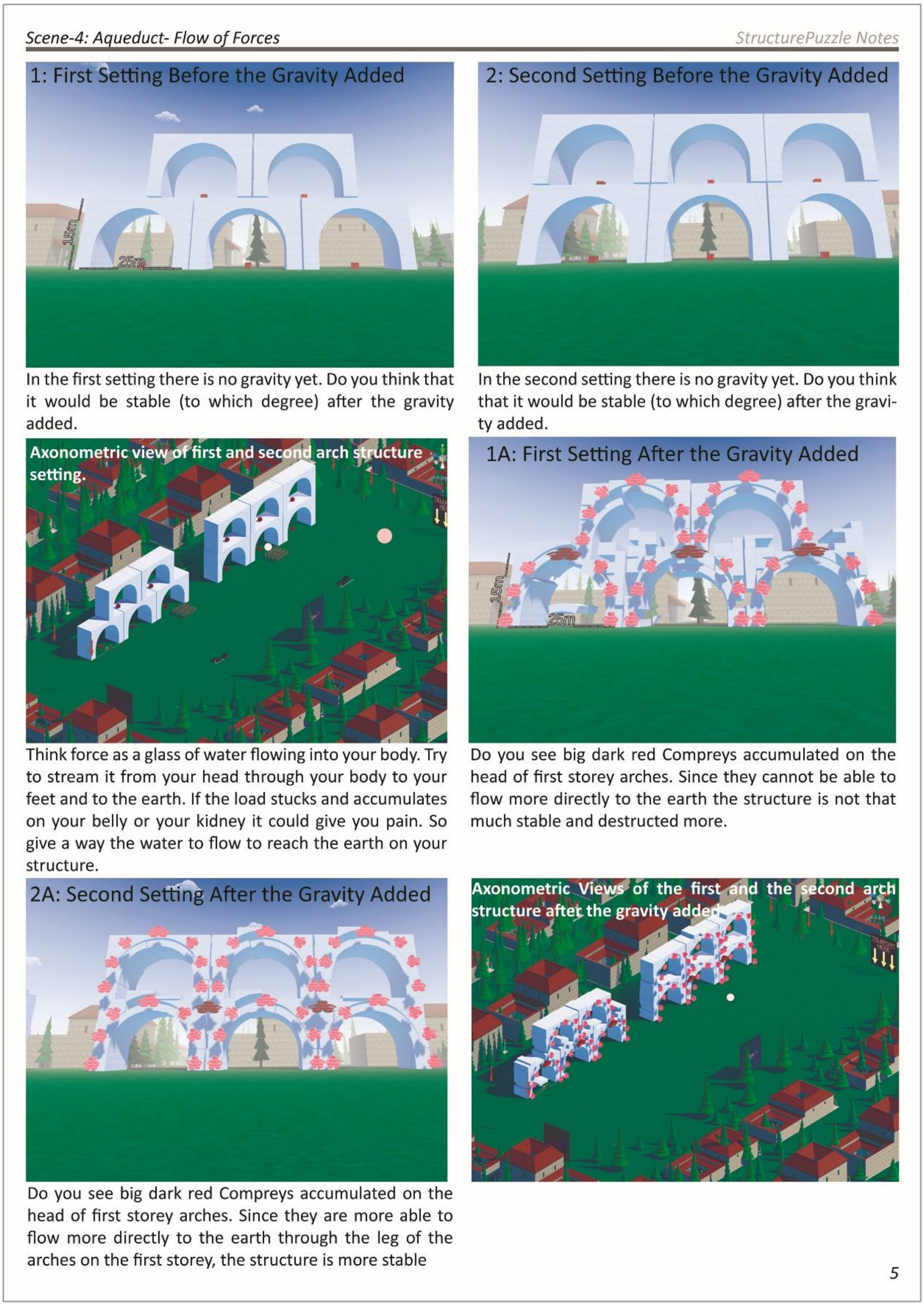
Catenary arch structure model of Sagrada Familia, Gaudi. After that he turned it upside down and it was the structure of the basilica.

Gateway Arch, Eero Saarinen
Catenary arch, 192m in height and the length

Creation of catenary arch by hanging the chain.

4

Figure A.4. Catenary Arch-Shaped by the Gravity


Scene-4: Aqueduct- Flow of Forces

StructurePuzzle Notes

1: First Setting Before the Gravity Added

15m

25m

In the first setting there is no gravity yet. Do you think that it would be stable (to which degree) after the gravity added.

2: Second Setting Before the Gravity Added

In the second setting there is no gravity yet. Do you think that it would be stable (to which degree) after the gravity added.

Axonometric view of first and second arch structure setting.

Think force as a glass of water flowing into your body. Try to stream it from your head through your body to your feet and to the earth. If the load stucks and accumulates on your belly or your kidney it could give you pain. So give a way the water to flow to reach the earth on your structure.

1A: First Setting After the Gravity Added

15m

25m

Do you see big dark red Compreys accumulated on the head of first storey arches. Since they cannot be able to flow more directly to the earth the structure is not that much stable and destructed more.

2A: Second Setting After the Gravity Added

Do you see big dark red Compreys accumulated on the head of first storey arches. Since they are more able to flow more directly to the earth through the leg of the arches on the first storey, the structure is more stable

Axonometric Views of the first and the second arch structure after the gravity added.

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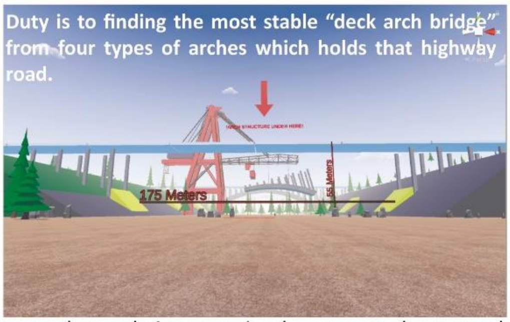
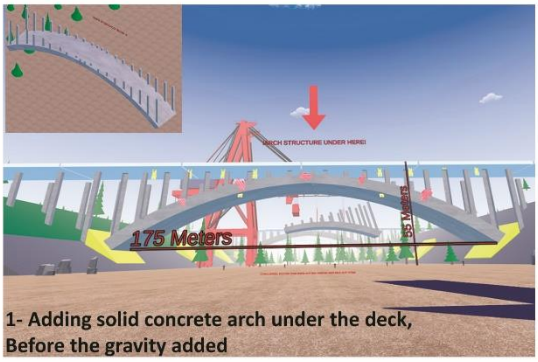
Figure A.5. Aqueduct- Flow of Forces

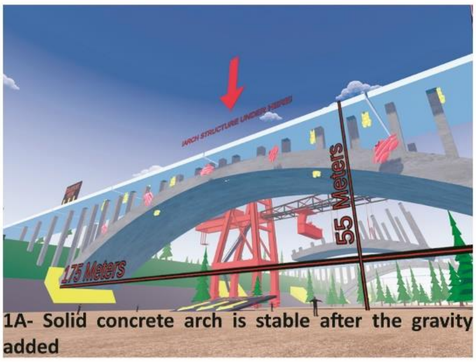
Scene-5: Deck Arch Bridge *StructurePuzzle Notes*



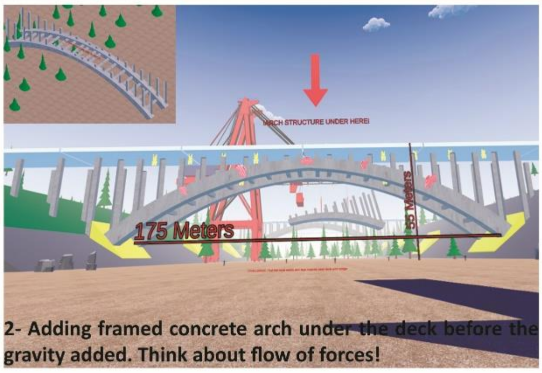
Arch bridges are one of the oldest types of bridges and have great natural strength. As you saw in other scenes, arches are used in long span bridge typology and other long span structures. There are different types of arch bridges. One of them is deck arch bridge which comprises an arch where the deck (road that is used by car, people...) is completely above the arch. Typically, modern arch bridges span between 60-250 meters of span. Span is the distance between two intermediate supports for a structure. The typically used ratio of rise-to-span for steel arch bridges is in the range of 1:5 to 1:6.

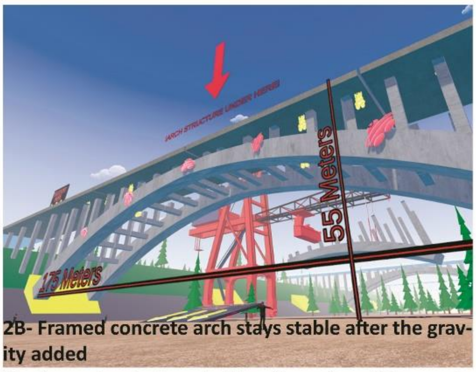


The area between the arch and the deck is known as the spandrel. Do you see Comprey? Or any Tensey?



The concrete arch is in compression.





The framed arch stays stable as it was in solid concrete arch. Which one of the arches are used more concrete? However both are as stable as each other right? So which one of them do you prefer to use? Yes, this is what engineering is :)

http://www.apliut.com/pages/aideenseignement/swapshop_Nimes07/desparbes%20_bridges.pdf
http://bmeeokepito-cd.bmeeok.hu/CD/%C3%96ssze_vissza_t%C3%A1rgyak/Ac%C3%A9lh%C3%ADd/Steel%20Bridges/steel/arch_bridge_design.pdf 6

Figure A.6. Deck Arch Bridge

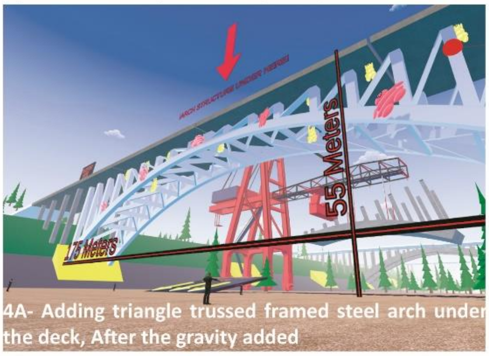
3- Adding framed steel arch under the deck, Before the gravity added

3A- Adding framed steel arch under the deck, After the gravity added

Since this framed arch is made out of steel, the thickness of an arch is more thinner than the concrete because of the more load bearing capacity of steel.

However, after the gravity added the framed steel arch could not stand well. What could be the reason for this? If you think steel as marshmellow and the concrete as cookie, marshmellow can be bent or compressed easily but can be more open for displacement against impacts. However, a cookie can only be compressed and hard to be displaced by the impact.
One of the reason is that, since steel is softer material than the concrete it could easily bend against impact, especially against compression. To cope with that, the perpendicular frames has to be strengthened by other steel supports. Which as you know by **triangular trusses** or so.

4- Adding triangle trussed framed steel arch under the deck, Before the gravity added



4A- Adding triangle trussed framed steel arch under the deck, After the gravity added

What will happen when the trusses are added to structure? Try to visualize the flow of forces on your mind. Which part is directing which force to which part and in the end through the earth?

After the gravity added to the scene the trussed framed steel deck arch bridge is more stable. Now the bridge is more flexible as a means of directing forces.

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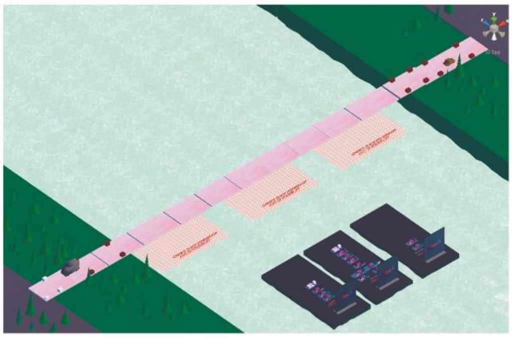
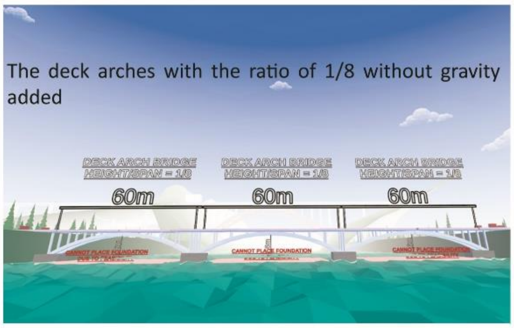
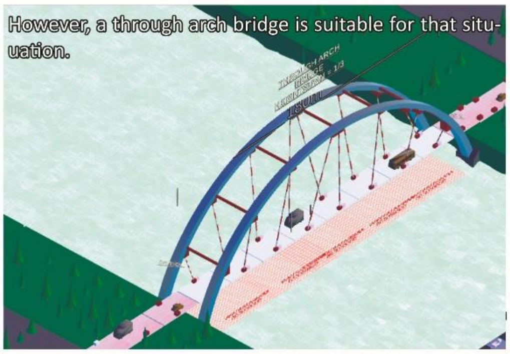
Figure A.7. Deck Arch Bridge

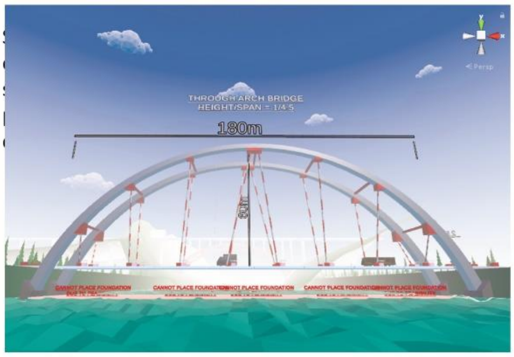


What type of bridge are you able design for the situation on the left picture. The span is 180 meters and the height difference between river surface and the topography is 7.meters. Try to design a deck bridge here.

Sometimes engineers are not allowed to design a deck arch bridge due to ratio between span length and height of an arch. The typically used ratio of rise-to-span for steel arch bridges is in the range of 1:5 to 1:6. However in the first example, this ratio of deck arches even if with 3 different arches are 1/8. And if it is wanted to be done with one arch the ratio is 180/7.5 = 24 So that this situation requires to design a through arch bridge.







This requires a structure that can both support the deck from the arch by tension rods, chains or cables and allow a gap in the arch, so the deck can pass through it. Moreover as it was in the trussed deck bridge example, there has to be several supports between two arches against wind and earthquake loads. The formation of arches does not have to be parallel to the deck, there are several types of through arch bridges.

http://bmeeokepito-cd.bmeeok.hu/CD/%C3%96ssze_vissza_t%C3%A1rgyak/Ac%C3%A9lh%C3%ADd/Steel%20Bridges/steel/arch_bridge_design.pdf

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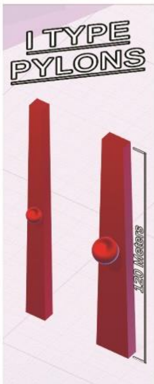
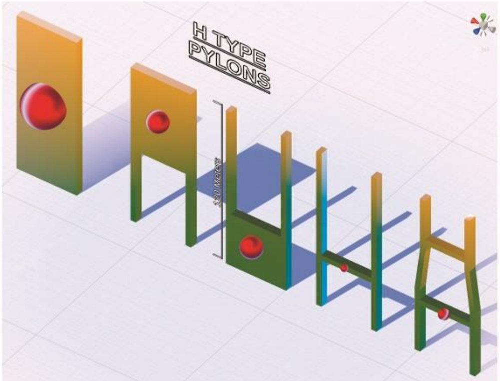
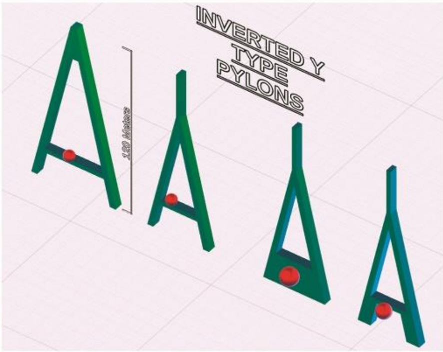
Figure A.8. Through Arch Bridge

Scene-7: Pylon Types Against the Wind *StructurePuzzle Notes*

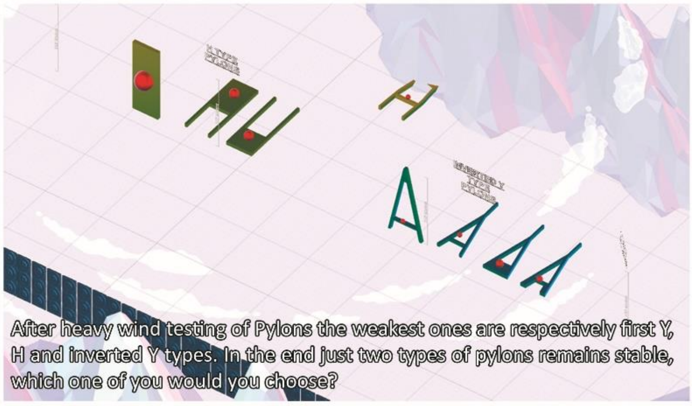






There is not only arch bridges is for long-span bridges to construct. Cable stayed and suspension bridges are other main typologies of long-span bridges. Different than the arch bridges these requires pylons and steel cables (large columns so to call). In this scene, we will understand the behaviours of various types of columns against loading, wind and earthquake. Pylon types are generally categorized under I,H,Y A, and inverted Y. Here you can see the red spheres on pylons which are indicating their weight and gravitational centers. Which one of the pylons would you think that be more stable against wind or earthquake?

Normally, as the gravitational center is close to ground we would expect that it would be to more stable against the external forces. However, it is not the all the case. For example, for the second Y type pylon in the image; the weight and the gravitational center seems enough to be stable against wind, however, the A type pylon is more stable against wind although the Y type is one of the most weak against the wind.



Moreover, for the earthquake loads, the damage probability descends in this order: A, Y, diamond, and H shape. The reason that H shape has the best performance is that it has the least damage probability for bearing displacement it performs relatively well against earthquakes. As you see there are different types of pylons for different needs according to regions that the bridge is going to be built upon.

-Earthquakes and Structures, Vol. 11, No. 4 (2016) 583-607 DOI: http://dx.doi.org/10.12989/eas.2016.11.4.583
-International Journal of Engineering Research & Technology (IJERT) IJERTIJERT ISSN: 2278-0181 IJERTV3IS100328 www.ijert.org Vol. 3 Issue 10, October- 2014

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Figure A.9. Pylon Types Against the Wind

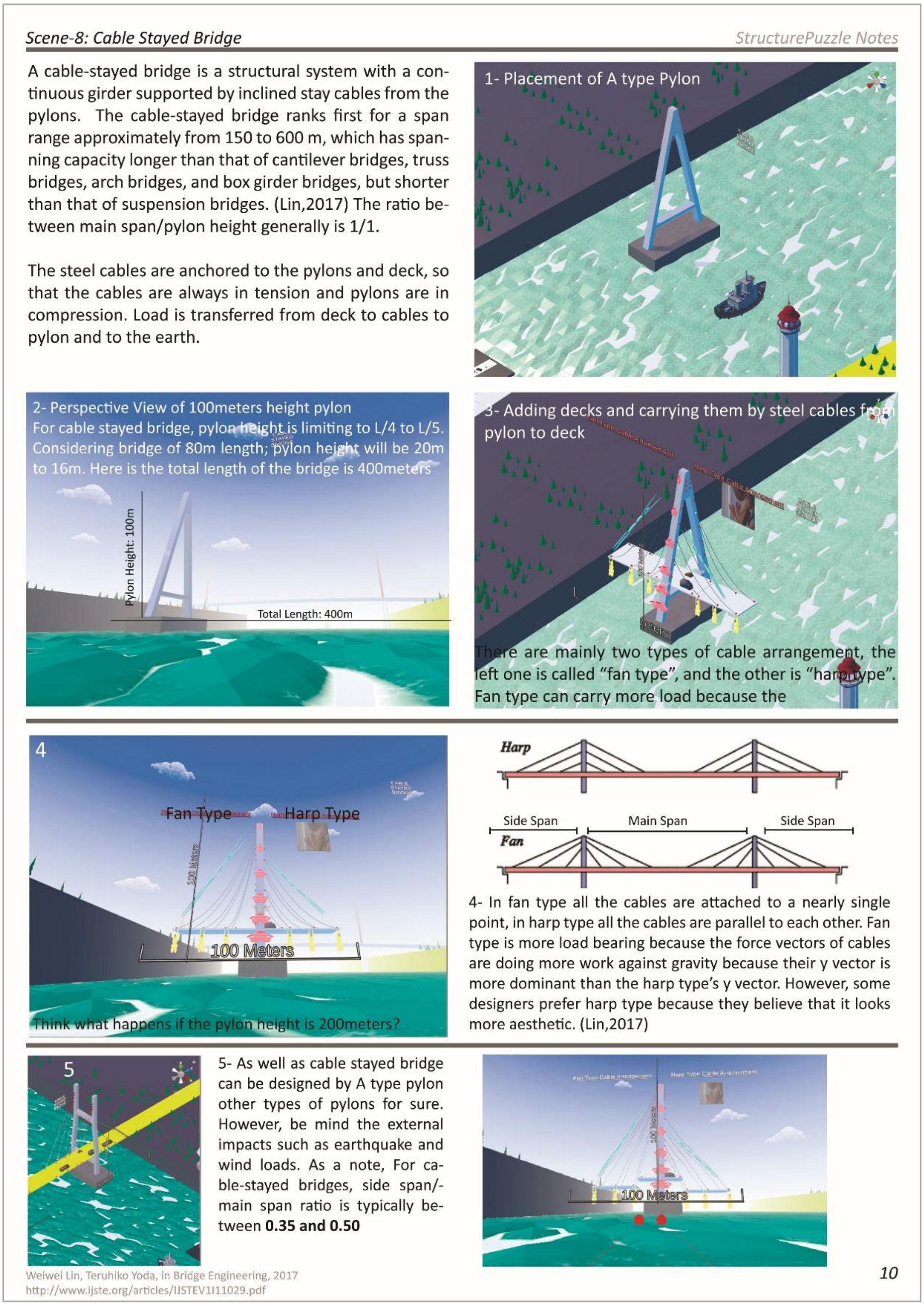
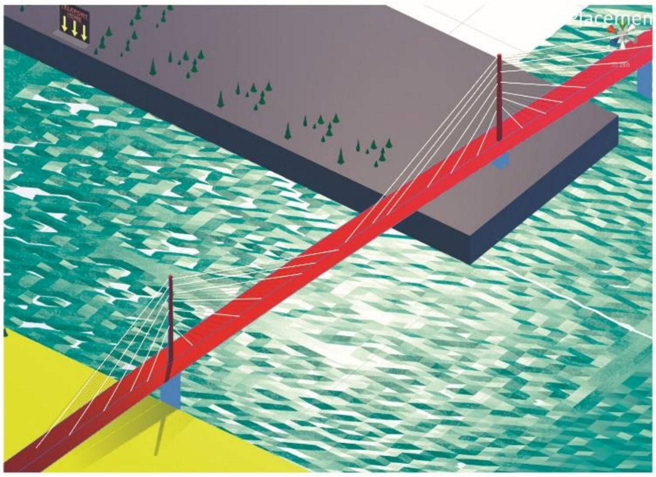
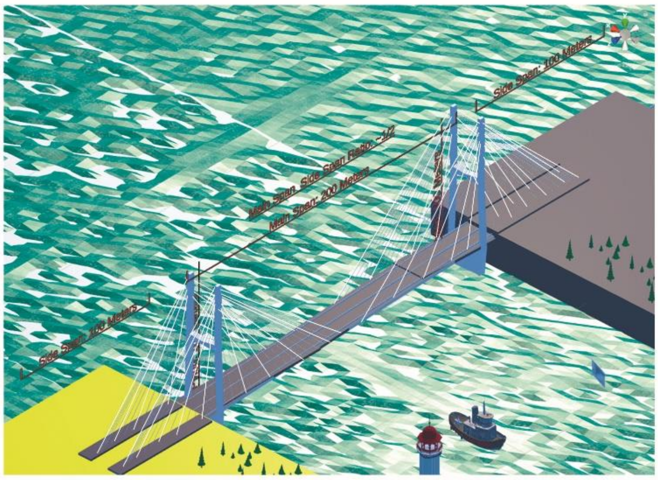


Figure A.10. Cable-Stayed Bridge

Scene-8: Cable Stayed Bridge *StructurePuzzle Notes*



Cable Stayed Bridge with I type pylons



Cable Stayed Bridge with H type pylons

Weiwei Lin, Teruhiko Yoda, in Bridge Engineering, 2017

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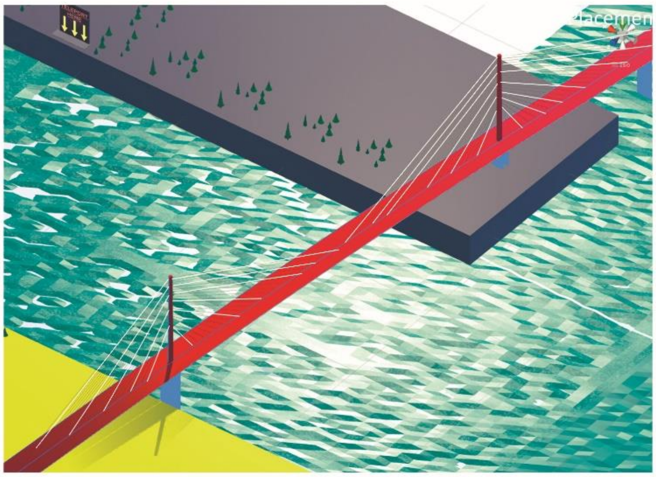
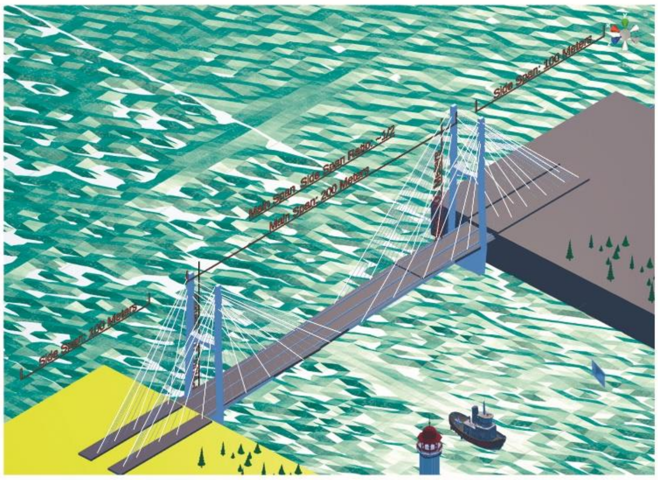
Figure A.11. Cable-Stayed Bridge



Cable Stayed Bridge with I type pylons



Cable Stayed Bridge with H type pylons

Figure A.12. Cable-Stayed Bridge

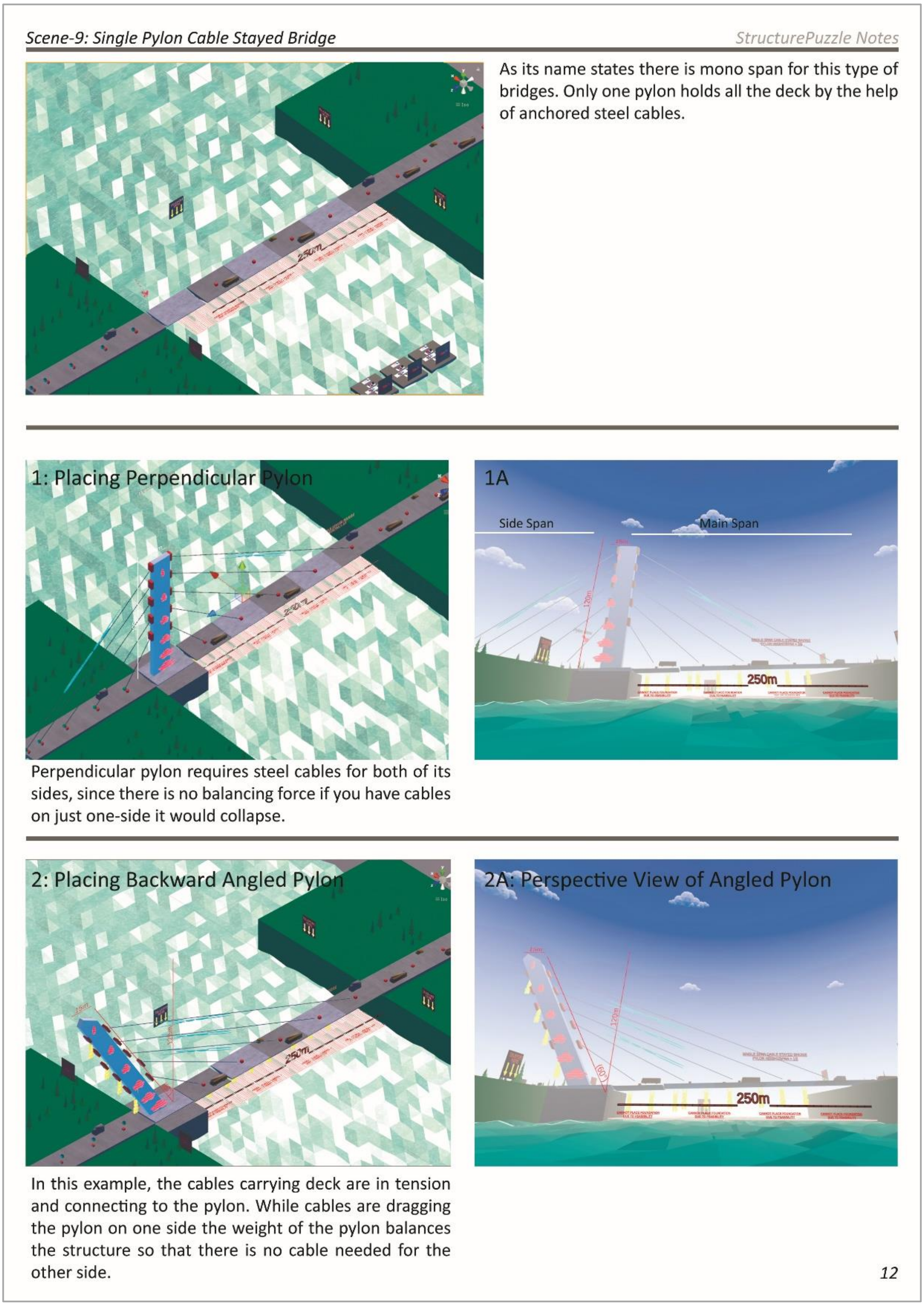
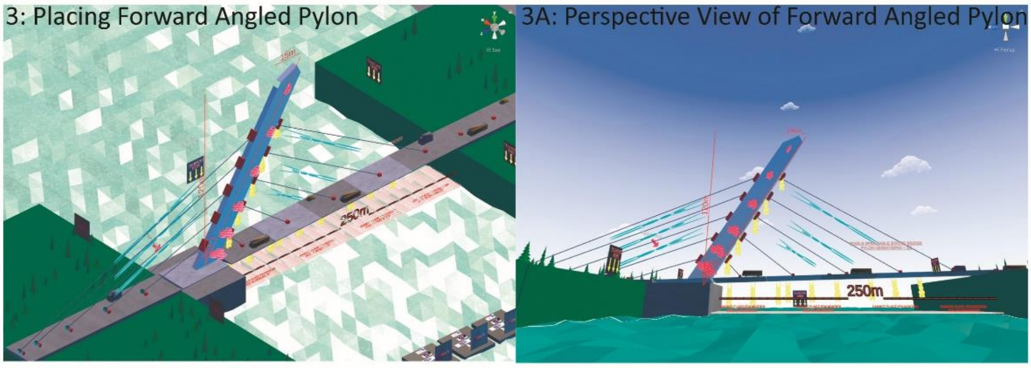


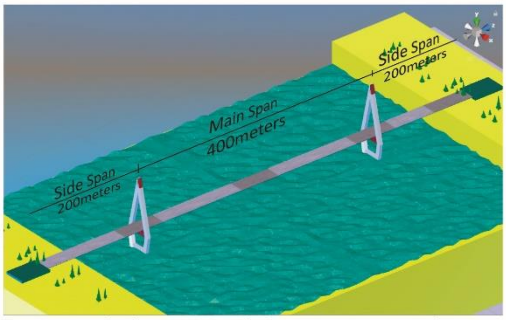
Figure A.13. Single Pylon Cable Stayed Bridge

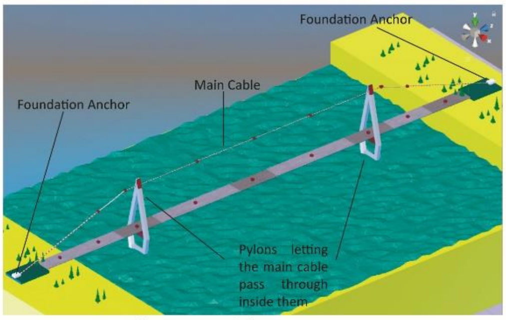


Forward angled pylon requires steel cables for both of its sides, since there is no balancing force if you have cables on just one-side to carry the deck it would collapse. Therefore other side also needs steel cables. Think of tension stress difference on the cables on both sides.

Figure A.14. Single Pylon Cable Stayed Bridge

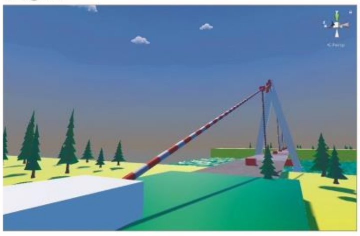
Scene-10: Suspension Bridge-Chavanon Viaduct *StructurePuzzle Notes*

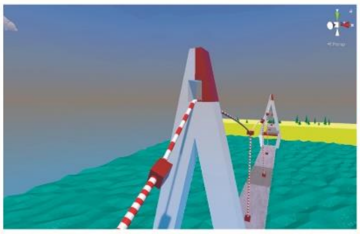


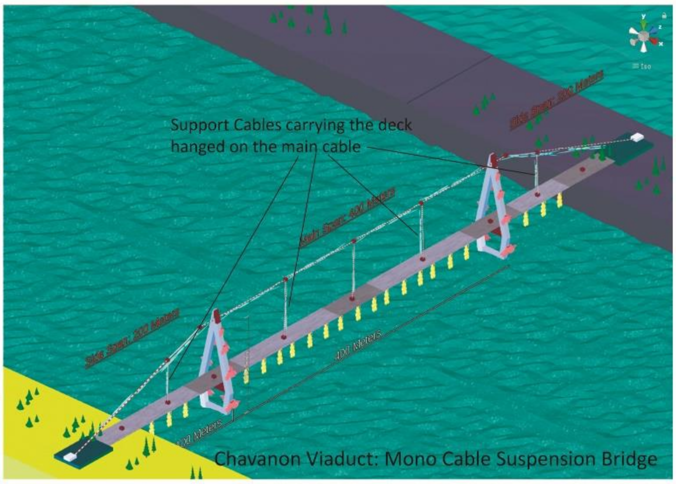


Suspension bridges are used if a span is more than 600 meters. On these span length it is economical to construct suspension bridges. A suspension bridge is one where cables (or ropes or chains) are strung across the
river (or whatever the obstacle happens to be) and the deck is suspended from these cables. Modern suspension bridges have two tall towers through which the cables arestrung. Thus, the towers are supporting the majority of the roadway's weight.

-Tower carries the main cables.
-Foundation and support anchors provides main cable to stay in tension.
-Suspension cables transfer load of the deck to main cable to tower to foundation and lastly to the earth
-Usually a ratio of pylon height to to total span is 1/9-1/10. Think if the pylons are 20 meters what will happen?







Golden Gate Double Cable Suspension Bridge
Main Span: 1280 meters
After carrying the deck the main cables are in the form of parabola, so that, the pylons have to be high enough to carry the deck.

Bogazici Bridge (Bosphorus) is also another Double Cable Suspension Bridge
Main Span: 1074 meters

http://www.wsdot.wa.gov/TNBhistory/Machine/machine1.htm
http://science.howstuffworks.com/bridge7.htm

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Figure A.15. Suspension Bridge- Chavanon Viaduct

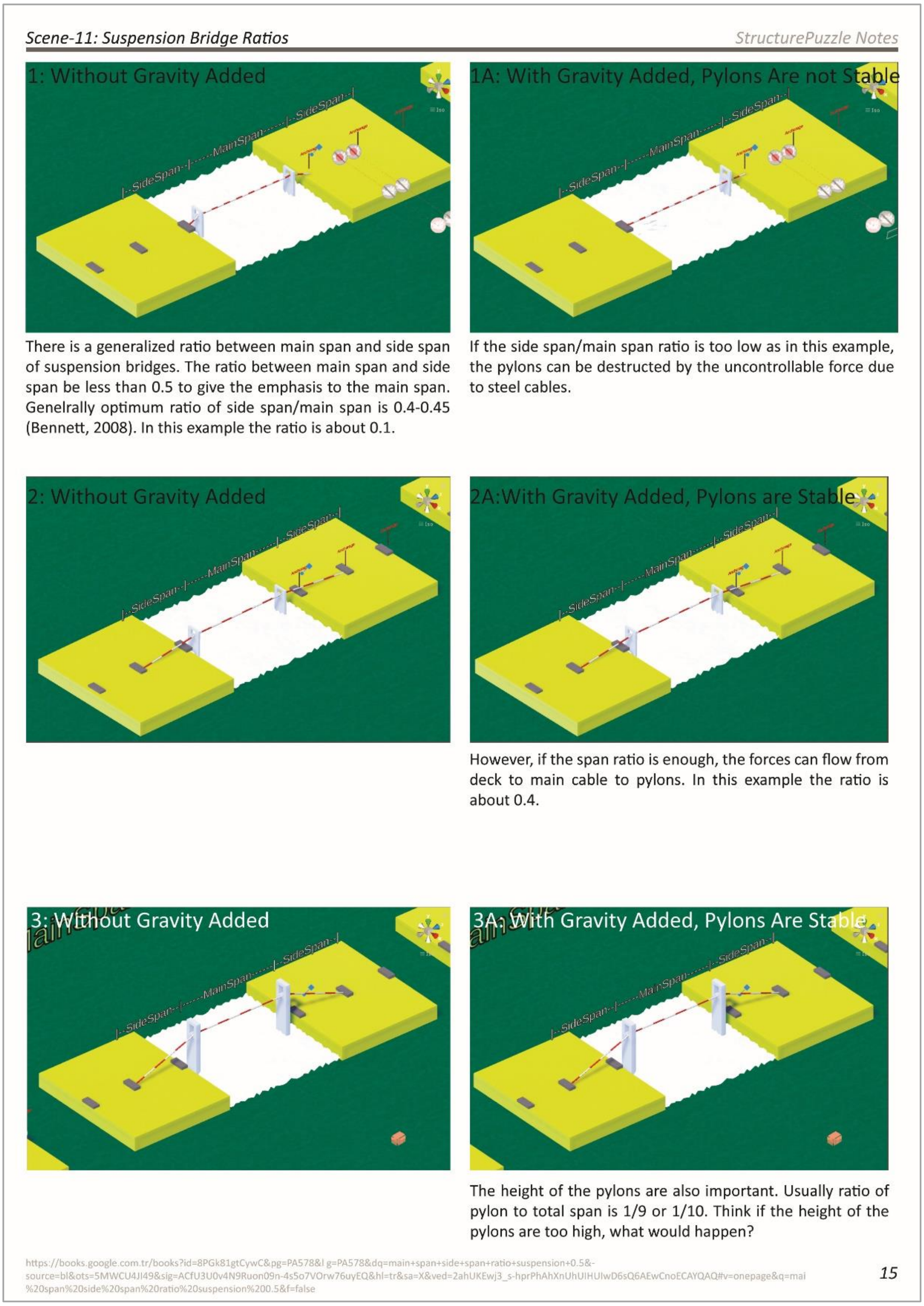

Figure A.16. Suspension Bridge Ratios

B. EXAMPLES OF DIAGNOSTIC ASSESSMENTS

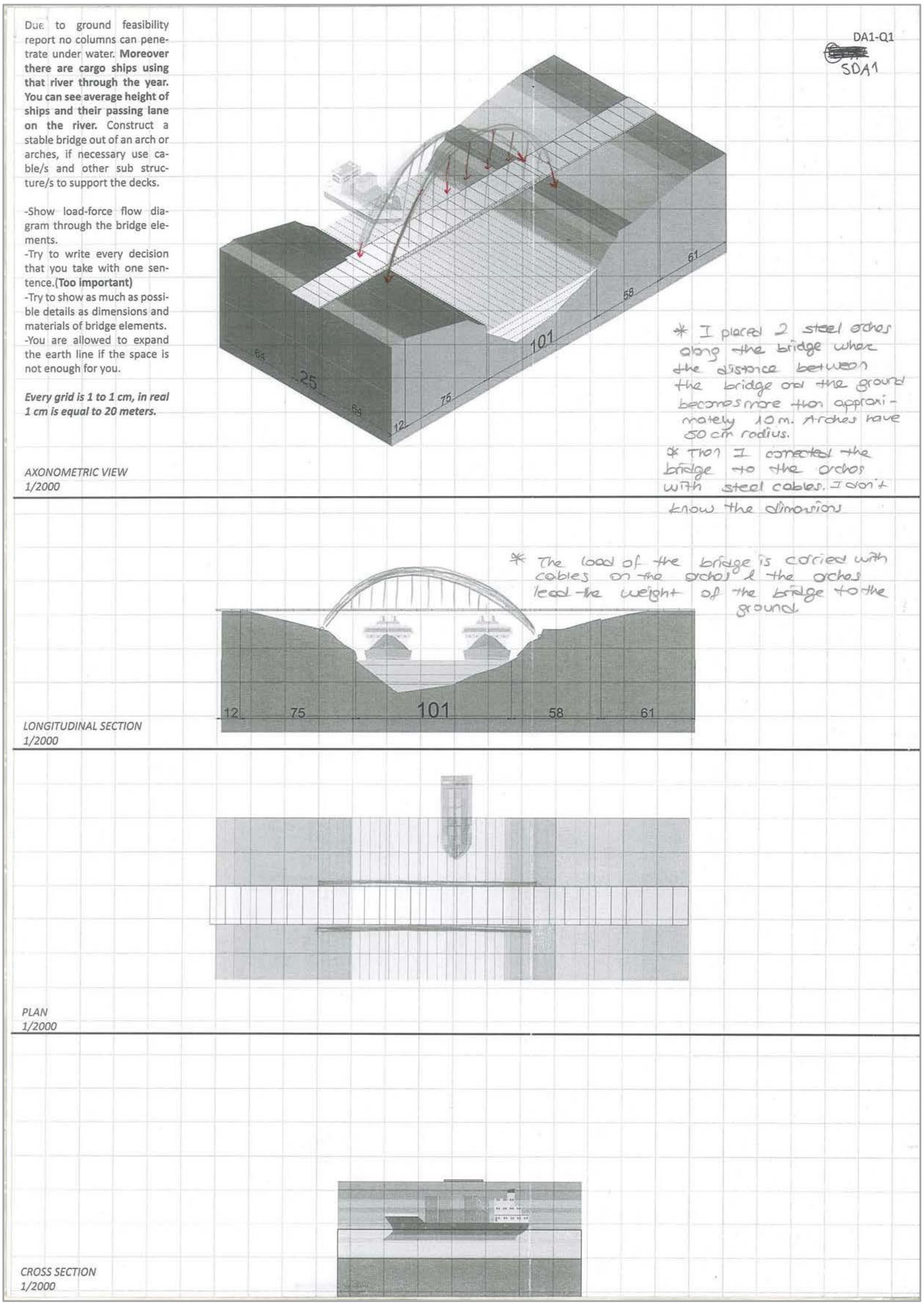

Figure B.1. Participant 5 DA-1 Arch Bridge Question

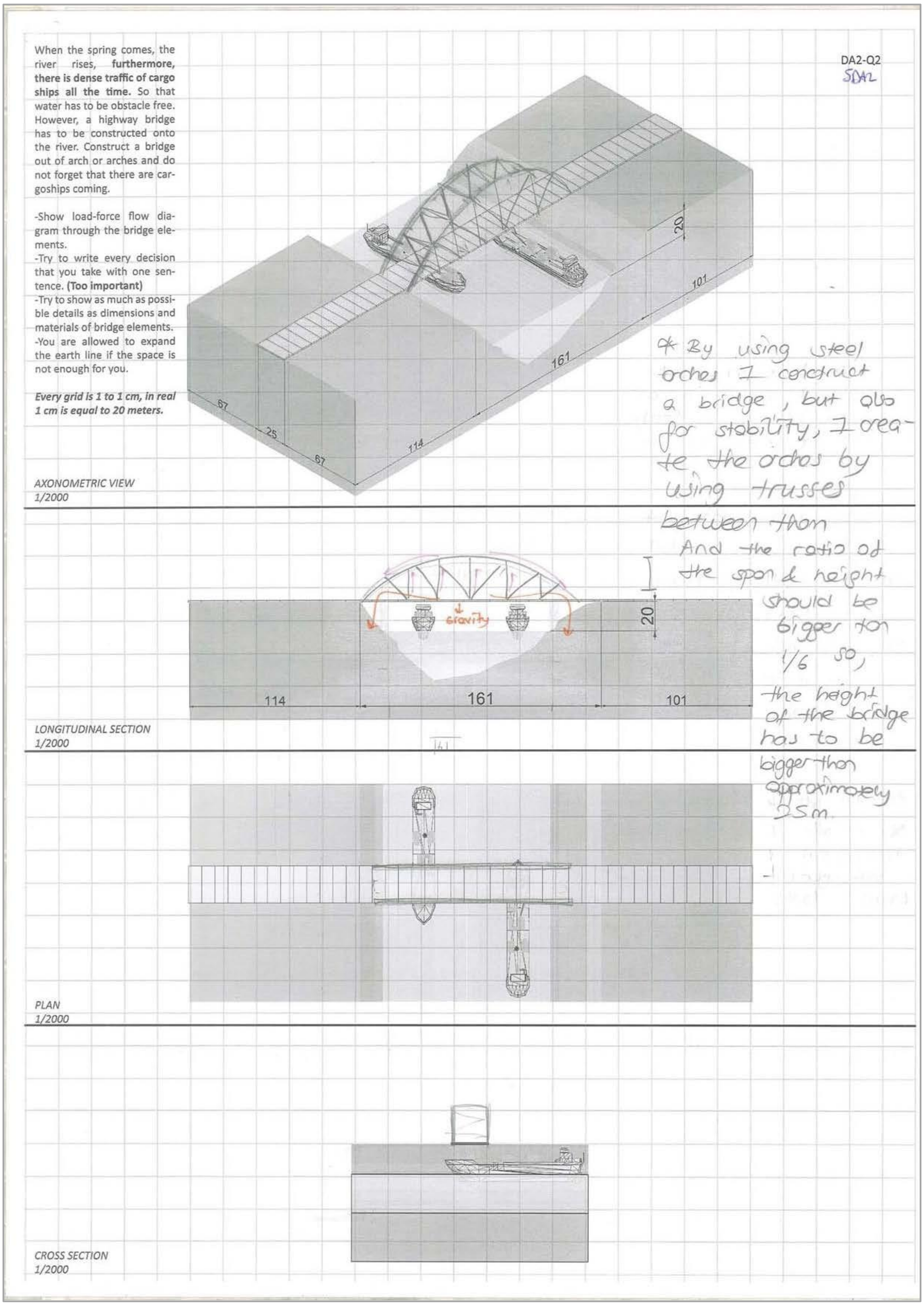

Figure B.2. Participant 5 DA-2 Arch Bridge Question- Having SPVR

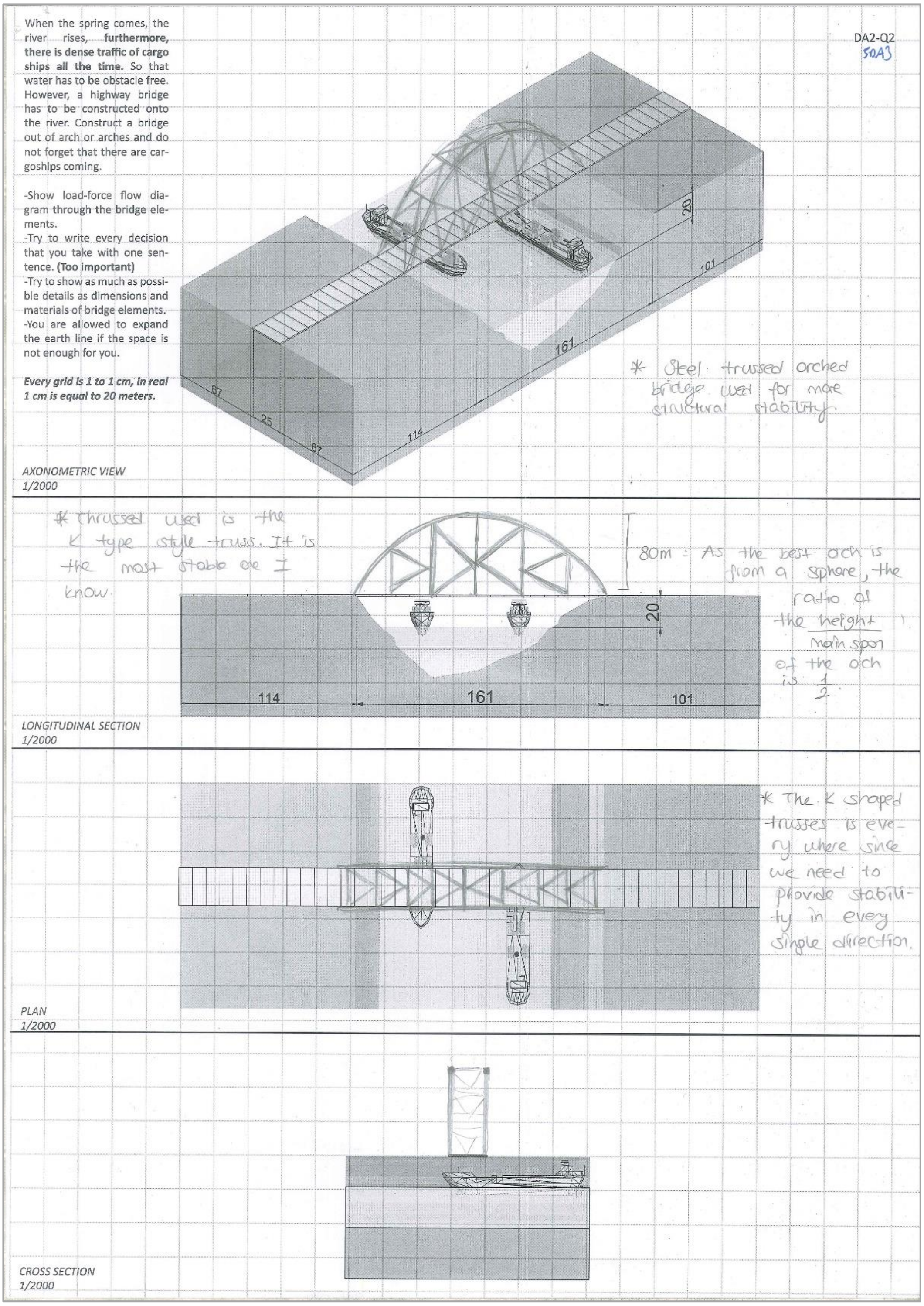

Figure B.3. Participant 5 DA-3 Arch Bridge Question- Second SPVR

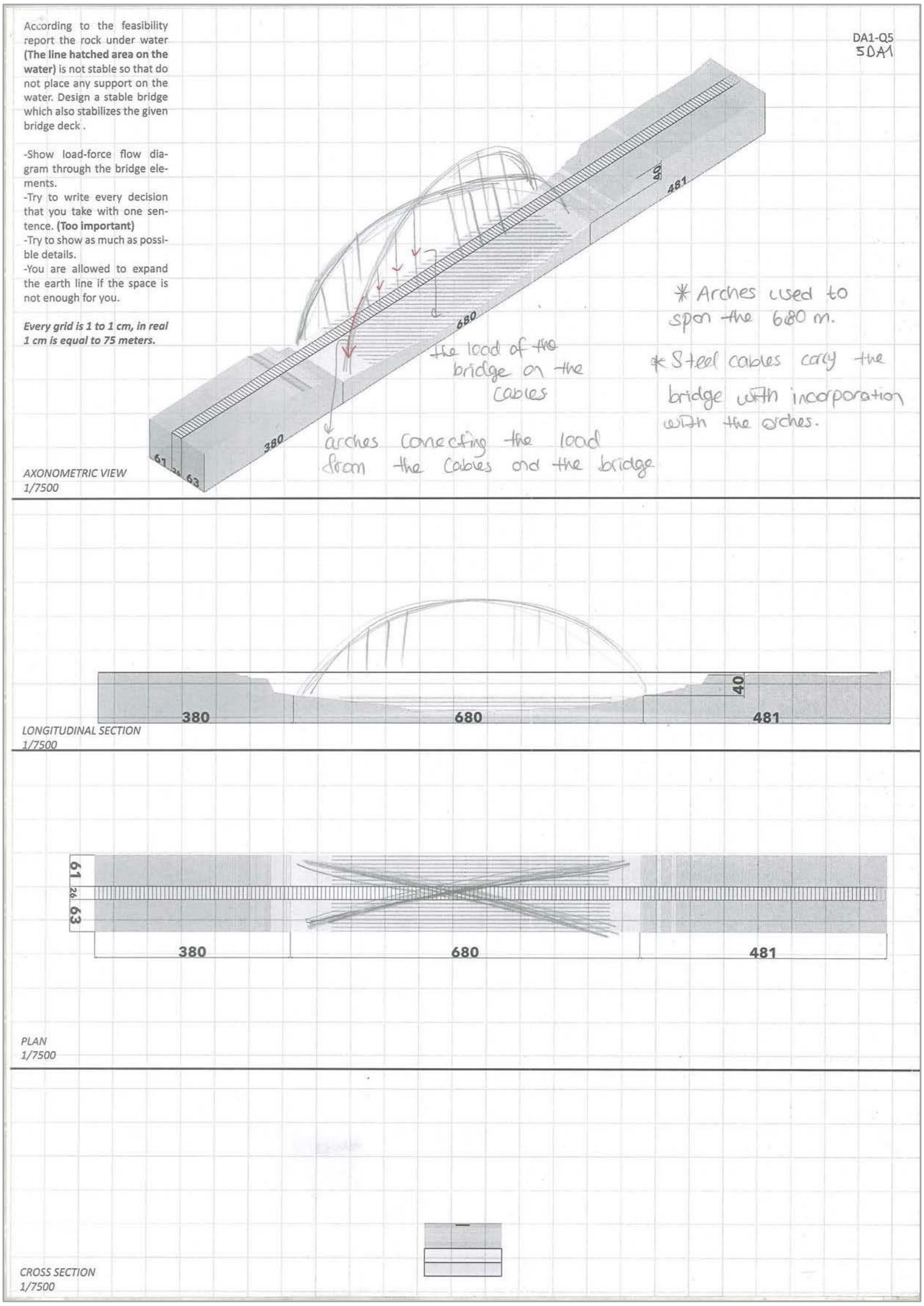

Figure B.4. Participant 5 DA-1 Suspension Bridge Question

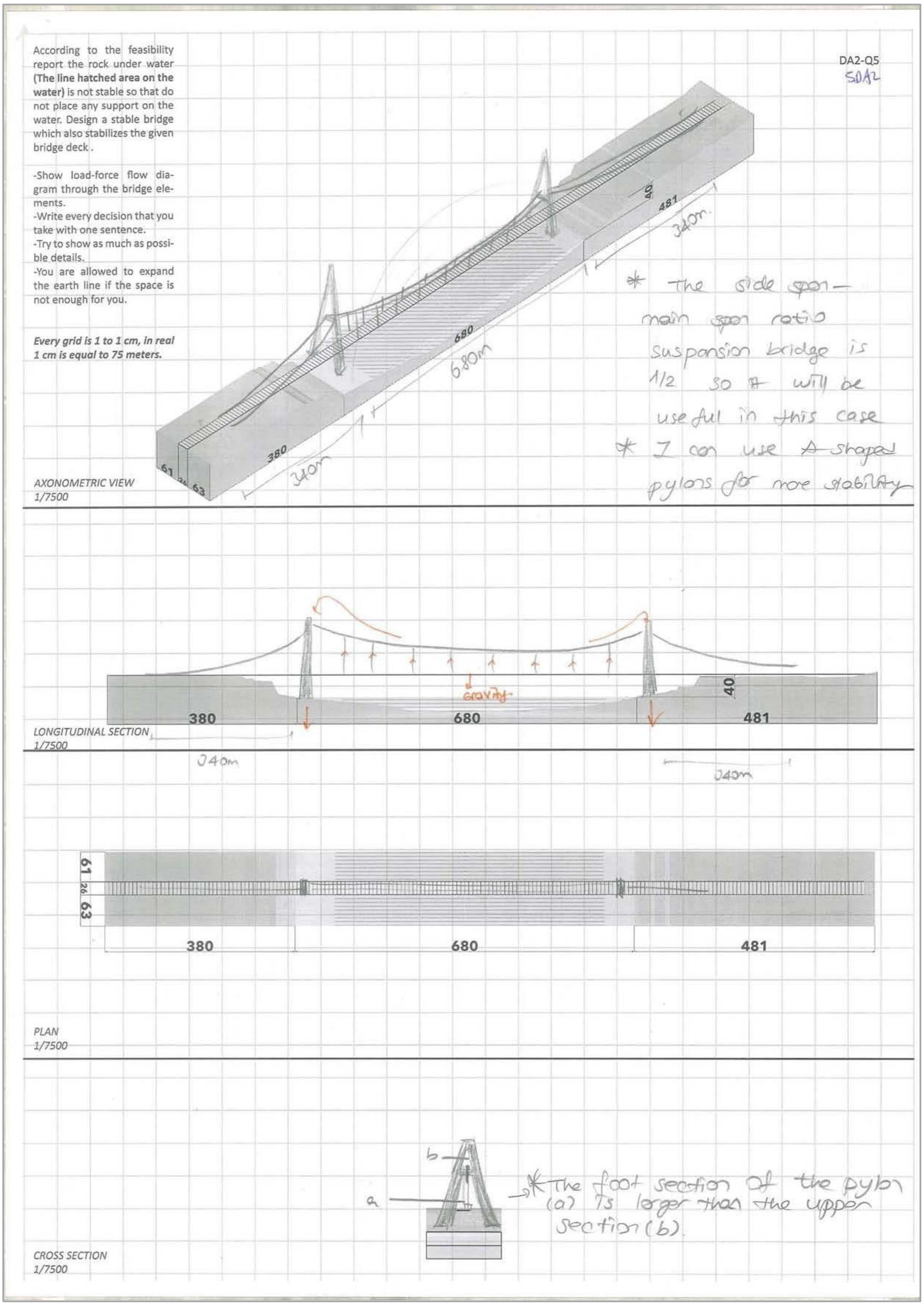

Figure B.5. Participant 5 DA-2 Suspension Bridge Question- After SPVR

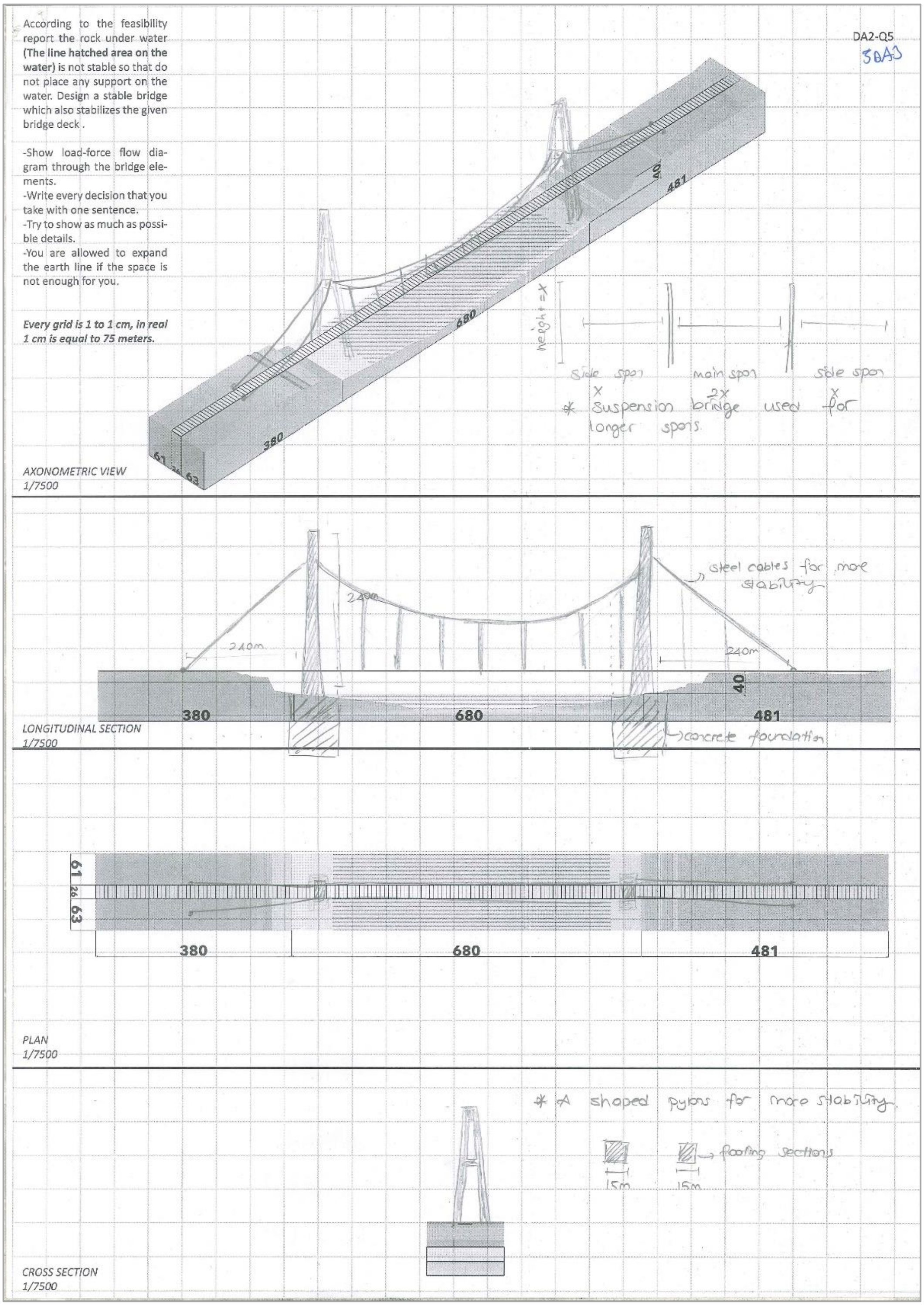

Figure B.6. Participant 5 DA-3 Suspension Bridge Question- Second SPVR

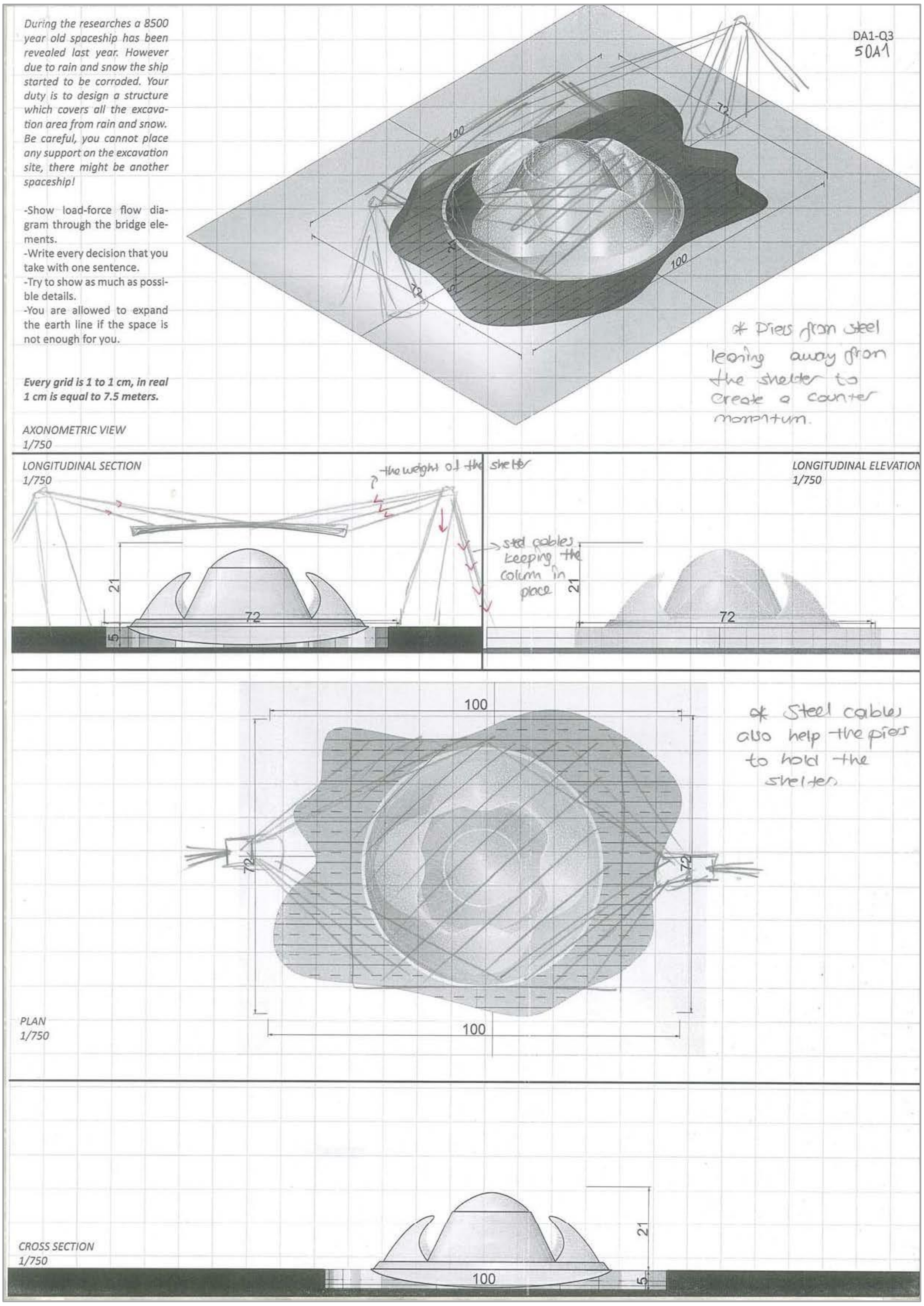

Figure B.7. Participant 5 DA-1 Long Span Covering Question

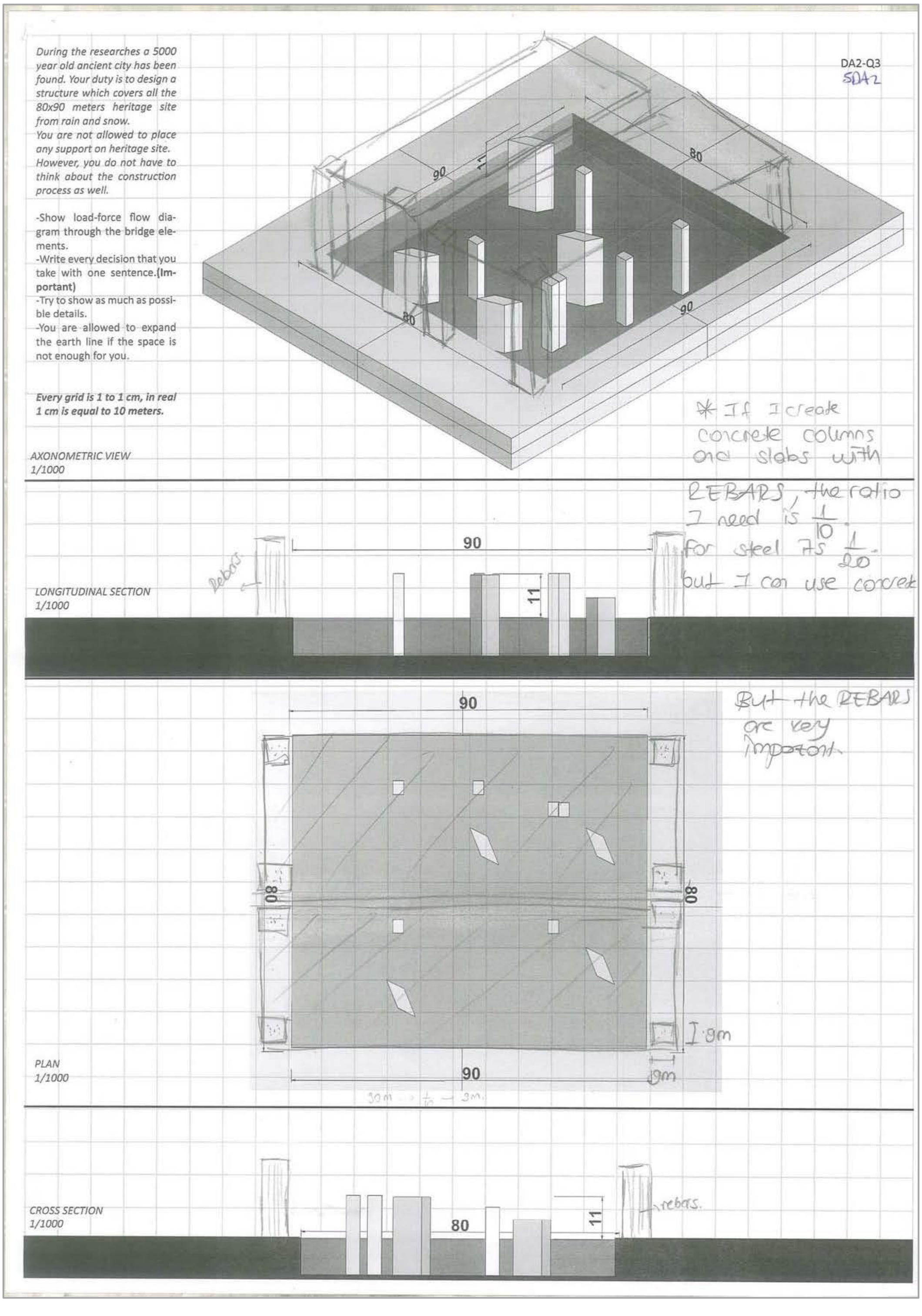

Figure B.8. Participant 5 DA-2 Long Span Covering Question- Having SPVR

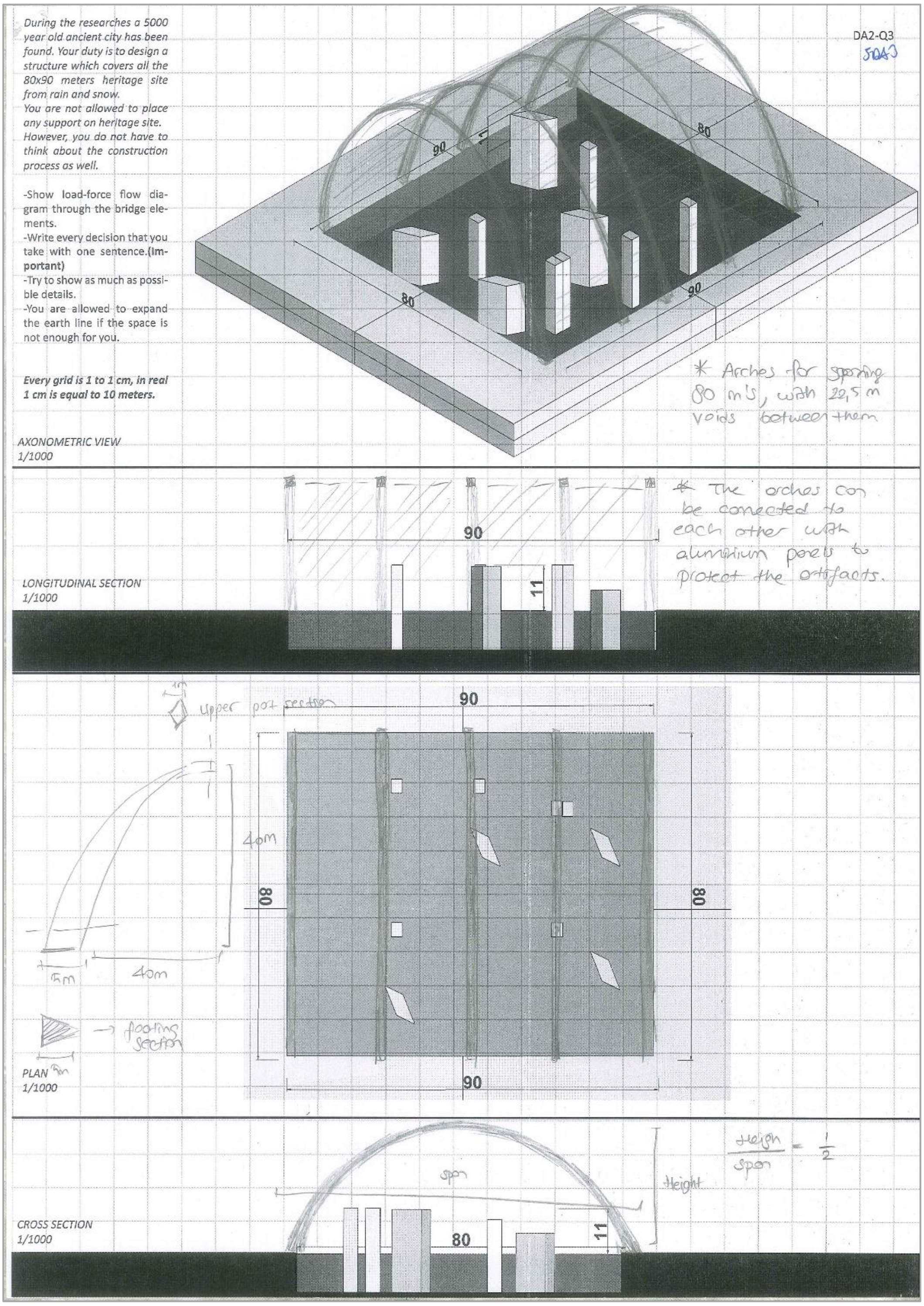

Figure B.9. Participant 5 DA-3 Long Span Covering Question- Second SPVR