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POTENTIAL OF VIRTUAL REALITY (VR) TECHNOLOGY FOR SAFETY TRAINING AND ACCIDENT PREVENTION IN CONSTRUCTION

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ABSTRACT

The construction industry is inherently risky, with accidents and injuries posing significant challenges to workers' safety and well-being. Traditional safety training methods, while valuable, may have limitations in effectively preparing workers for the complex and hazardous environments they encounter. This study investigates the potential of virtual reality (VR) technology as an innovative approach to safety training and accident prevention in construction. Using a combination of literature review and empirical research, this study examines the effectiveness and feasibility of VR technology in simulating real-life construction scenarios, providing immersive training experiences, and enhancing workers' safety skills. The research explores the current state of VR adoption in safety training programs, identifies barriers to implementation, and proposes strategies for overcoming challenges. Qualitative design was used as the methodology and six industry experts were interviewed under semi-structured interviews. Key findings highlight the promising role of VR technology in improving safety awareness, hazard recognition, and emergency response among construction workers. Additionally, the study underscores the need for comprehensive training programs that integrate VR simulations with traditional methods to maximise effectiveness and engagement. Implications for practice include recommendations for safety training institutes, construction companies, and policymakers to invest in VR technology, develop tailored training modules, and foster a culture of safety consciousness within the industry. The study suggests avenues for future research to explore the long-term impact of VR training on accident rates, worker behaviour, and organisational safety culture. Overall, this research contributes to advancing safety practices in the construction industry by harnessing the potential of VR technology to prevent accidents, mitigate risks, and protect the well-being of workers.

Keywords: *Construction; Safety Training; Simulator Base Training; Sri Lankan Safety Training Program; Virtual Reality.*

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1. INTRODUCTION

The history of the construction industry can be traced back to the time of huts and shelters, where houses, tools, bridges, and other structures were constructed by hand using simple tools. The word "construction" originates from the Latin word "construccioun" (Thomson, 1984), which encompasses the art and science of creating objects, systems, or organisations, primarily through building. The construction industry plays a vital role in a country's social welfare, national economy, and job market (Baraka et al., 2019), with various professionals contributing, such as Engineers, Architects, Quantity Surveyors, Land Surveyors, Planners, and various types of labourers.

The construction industry is generally divided into four sectors i.e., (i) residential building construction, (ii) commercial construction, (iii) industrial construction, and (iv) heavy construction. Residential building construction includes individual houses or private dwellings, lodging or rooming houses, dormitories, apartments, and hotels. In the commercial construction sector, projects range from small-scale to medium-scale and large-scale commercial buildings. Heavy construction, known as civil engineering, encompasses infrastructure projects such as public works, bridges, waterways, dams, and all types of roads. Industrial construction involves the construction of various industrial works, plants, and power generation facilities (Anupoju, 2020).

The Sri Lankan construction industry holds significant importance for the country's Gross National Income (GNI) and Gross Domestic Product (GDP). Over the last decade, investments in the construction industry have had a substantial impact on the Sri Lankan economy. In the fourth quarter of 2016, the Sri Lankan construction industry achieved record-high GDP figures. The construction industry makes a considerable contribution to both global and local GDP and GNI (Yuen et al., 2005). Productivity is a key indicator of economic performance for any industry, including construction (Naismith et al., 2016). The strong correlation between the construction industry and GDP/GNI is evident in Sri Lanka, where the construction industry has significantly influenced the country's gross national income over the past three decades (Wedikkara & Devapriya, 2000).

According to global macroeconomic models and analysts, from 2010 to 2019, the construction industry in Sri Lanka generated an average GDP of 142,507.63 LKR million. The fourth quarter of 2017 saw a peak of 190,372 LKR million, while the second quarter of 2010 marked a low of 77,176 LKR million. Projections indicate that by the first quarter of 2020, the industry's value is predicted to reach 166,736.00 LKR million (“Sri Lanka GDP from construction”, n.d.).

On the other hand, the construction industry is widely recognised as one of the most perilous fields to work in. Within this industry, certain roles, such as roofers, excavator drivers, steelworkers, and logging workers, are among the highest-risk occupations globally. Various factors contribute to the increasing rate of construction accidents. These include the inherently high-risk nature of construction tasks, limited safety knowledge among workers and professionals, lack of on-site safety awareness and technical education (Saleh & Pendley, 2012), the transient nature of the industry, inadequate resource management at construction sites, and the complexity of organisational structures within the industry (Rameezdeen et al., 2006). Unsafe working conditions, insufficient safety training, failure to follow safety protocols, negligence, and lack of adherence to safety regulations also play significant roles (Perera et al., 2017).

Effective recording systems for occupational accidents are crucial within the construction industry of any country. Such systems serve as valuable management tools for risk assessment, aiding in the prevention of fatalities, injuries, and health hazards, as well as minimising costs associated with accidental losses. However, the absence of robust reporting procedures can lead to shortcomings in accident management (Fu et al., 2018). Safety issues significantly impact construction industry productivity, resulting in waste, health problems, and safety hazards (Kenley, 2014). Moreover, construction worker injuries have broad adverse effects, including personal suffering, construction delays, productivity losses, reduced workforce morale, increased insurance premiums, and potential liability lawsuits (Rameezdeen et al., 2006).

A risk in the construction industry is defined as a probable event with identifiable causes and potential impacts (Baraka et al., 2019). The level of risk fluctuates throughout a construction project, influenced by various project circumstances. According to construction fatality statistics, falls account for 33.5% of accidents and injuries, followed by being struck by objects (11.1%), electrocutions (8.5%), and being caught in or between objects (5.5%) (Jones, 2020). Globally, approximately one in every five construction workers experiences accidents or fatalities. Poor training, failure to follow safety protocols, negligence, and carelessness are identified as significant factors contributing to construction accidents (International Labour Organization [ILO], 2019). The International Labour Organization (ILO) estimates that 2.3 million workers worldwide suffer work-related accidents annually, resulting in 6,000 deaths daily (ILO, 2019). In Sri Lanka, construction site accidents have increased between 2009 and 2012, with the ILO estimating that accidents cost approximately 4% of a country's Gross National Product (GNP) (Wijekoon, 2016).

Improving safety education in the construction industry is crucial. Safety training is paramount in reducing accidents and protecting workers. Several safety training institutions in Sri Lanka offer programs such as National Occupational Safety and Health, Advanced Construction Training Academy, Construction Industry Development Authority, Safety Global, Colombo International Nautical and Engineering College, OSHA Training Courses, and Occupation Safety and Health Management, among others. Utilising virtual reality (VR) technology for safety training offers advantages such as exposure to fewer real-world hazards, increased efficiency, and enhanced worker confidence. VR training can reduce training costs, accident rates, and associated expenses, while providing comprehensive knowledge of Personal Protective Equipment (PPE) and safety procedures (Sacks et al., 2013).

The construction industry in Sri Lanka, resembling many developing countries, faces challenges in safety education and management. Safety education is vital for reducing fatalities and enhancing construction productivity. Accidents in the Sri Lankan construction industry is commonly caused by factors such as vehicle and machinery use, slips, falls from heights, collapses, and exposure to hazardous materials (Spellman, 2020).

VR technology has evolved significantly since its inception in the 1960s, particularly in gaming and educational applications. VR simulations offer immersive experiences that can enhance learning and training in various industries, including construction. In the construction sector, VR training can simulate real-world scenarios, providing valuable experiential learning without the need for physical site visits.

Unplanned events in the construction industry are classified as accidents (Laufer & Ledbetter, 1986), highlighting the paramount importance of safety in construction projects. Work-related injuries result in significant productivity losses for construction companies worldwide, emphasising the necessity of prioritising safety training in every construction project (Jones, 2020). However, there is no evidence that VR has been adopted in the Sri Lankan construction industry. Hence, this research aims to identify the current state of VR adoption in safety training programs, identifies barriers to implementation, and proposes strategies for overcoming challenges to improve construction safety training and mitigate the adverse impacts of accidents on construction productivity.

2. LITERATURE REVIEW

2.1 OVERVIEW OF VIRTUAL REALITY

The concept of VR is one of the most successful simulator systems globally. The first VR/AR head-mounted display was founded by Ivan Sutherland and his student Bob Sproull in 1968 (Dom, 2018). Although the first head-mounted display was established in 1968, the VR concept traces back to the 19th century. VR concept originated from panoramic paintings, which aimed to create illusions of being somewhere we are not ("History of virtual reality", n.d.). Panoramic paintings, also known as 360-degree murals, provided viewers with a sense of immersion in historical events or scenes.

Following 1929, numerous companies began to explore VR technology, resulting in various innovations. For instance, in 1960, the first Head-Mounted Display (HMD) was introduced, followed by the first motion tracking HMD and video screens for each eye in 1961. Ivan Sutherland conceptualised the VR room in 1965, and in 1966, Thomas Furness developed a military engineer flight simulator. In 1968, Sutherland and his student created the first VR HMD with 3D models that changed with head movement. Myron Krueger introduced artificial reality in 1969, and General Electric built the first flight simulator with a 180-degree field of vision in 1972.

The 1970s and 1980s witnessed significant advancements, including the creation of the first interactive VR platform in 1977 (Aspen Movie Map), McDonnell-Douglas Corporation's VITAL helmet for military use in 1979, and stereo vision glasses in 1980. Sayre gloves were developed by Sandin and Defanti in 1982, followed by the introduction of VR goggles and gloves by Jaron Lanier and Thomas Zimmermen in 1985. The super cockpit, a flight simulator with 3D maps and real-time sound, was created in 1986. NASA integrated audio elements with the Power Glove in 1989, and in 1991, they developed Computer Simulated Teleportation, the first mass-produced VR entertainment system.

The 1990s saw the launch of the Virtual Boy, the first portable console to display 3D graphics in 1995, and the first PC-based cube room in 2001. Google introduced Street View with stereoscopic 3D mode in 2007 and 2010. Sony launched PlayStation 4 (PS4) in 2014, while Google introduced a low-cost and do-it-yourself stereoscopic system. Samsung developed a VR headset for Galaxy smartphones in 2014. In 2015, the Wall Street Journal launched a VR roller coaster, and BBC created a 360-degree video. HTC introduced the HTC VIVE Steam VR headset in 2016, allowing users to move freely in space. Since 2016, many companies have developed their own VR headsets, including HTC, Google, Apple, Amazon, Microsoft, Sony, Samsung, and Facebook.

2.2 TYPES OF SENSORS AND SOFTWIRES RELATED WITH VIRTUAL REALITY

All types of sensors contribute to providing real-time experiences for users (Teja, 2017). Electromagnetic sensors utilise electromagnetic fields and a source system. These sensors rely on the fixed position of the source and previously known items. Acoustic sensors function similarly to electromagnetic sensors, yet they differ in that they transmit high-frequency sound to the receiver. Optical sensors are crucial for VR and AR technology, aiding in motion tracking and optical motion capture. These sensors consist of various cameras, which track the position of markers in space by observing their positions in the field of view of each camera. These systems employ different monitoring principles, often utilising markers made of reflective material. Infrared-sensitive cameras monitor these markers or body movements in space. The cameras must be calibrated, meaning their overall position and orientation must be known. By combining the 2D tracking position of markers with information about the location and characteristics of each camera, the 3D position of markers can be accurately determined (Cvetković, 2021). Various sensor types are involved in Virtual Environments (VE).

VR development software includes paradigms such as Multigen, Perillith Industriell, VRML, Wild Tangent, 3Dstate, and 3D game engines (Thabet et al., 2002). Other notable software platforms include Unity, Amazon Sumerian, the Google VR developer portal, Unreal Engine 4 (UE4), CRYENGINE, Blender, 3Ds Max, SketchUp Studio, Maya, and Oculus Medium, among others (Davies, n.d.).

2.3 USAGE OF VIRTUAL REALITY IN THE INDUSTRIES

VR is evolving across various industries for different purposes (Shang et al., 2012). They further emphasised that the automotive industry uses VR technology for design and engineering reviews. Engineers and designers utilise VR technology to reduce the number of prototypes built per vehicle line (Korkut & Surer, 2023). The authors further mentioned that many vehicle manufacturing companies, such as BMW and Jaguar Land Rover, are adopting this technology at an early stage. In the healthcare industry, VR technology is being used in innovative ways (Qu et al., 2022). They further emphasised that health professionals nowadays use virtual human body parts for treatments. These virtual body parts are created to resemble real bodies and injuries closely. VR technology is known for its effectiveness in treating PTSD and anxiety.

The retail industry is using VR technology to enhance the shopping experience (Nantel, 2004). The author further mentioned that “in online shopping, we can’t try on clothes, shoes, etc., before buying them. This can lead to items not meeting requirements in terms of size, colour, etc”. With VR technology in the retail industry, customers can decide on clothes with body-scanning, providing different types and designs at one point. In the tourism industry, VR technology is used to create virtual maps for tourists (González-Rodríguez et al., 2020). They further emphasised that these maps include visiting places, hotels, restaurants, tourist landmarks, etc. In the real estate industry, VR helps reduce the time and money for clients (Ullah et al., 2018). The authors further mentioned that clients can look around properties virtually, mitigating the time spent visiting properties physically. In the construction industry, VR technology is used for various purposes, with architecture being the most common. VR helps visualise design models as real concepts before they are built. The advantage is that when a client needs to change some aspects of the building or home, it only affects the design (Guo et al., 2018). The Learning and Development (L&D) industry uses VR technology to provide training and soft skills for students. The sports and gaming industry allows viewers to watch their favourites and play games with 360 or 180-degree screens. Art can be created using VR painting tools, and it is also used for events and conference meetings. One of the popular industries using VR is law enforcement. Many countries now use VR and AR technology for military and police force training (Thompson, 2024). Rokooei et al. (2023), further mentioned that there is a high potential to use VR in safety training programme in the world.

3. RESEARCH METHODOLOGY

Every research study is based on a unique approach. During research, the primary goal is to find a method to address the study objectives. In making this decision, it is essential to first determine the type and availability of information needed to meet these objectives. The main strategies are typically qualitative and quantitative, with a combination of these two called mixed strategies. This research is based on the qualitative research strategy. in-depth interviews, questionnaires, focus groups, ethnographic research, content analysis, and case study research are examples of qualitative research methodologies commonly used.

The interview guideline comprised two parts; one to evaluate demographic factors, and the other to identify the potential of implementing VR technology in the construction field. The collected data is presented using both graphical and numerical methods.

Firstly, the data presentation focuses on the demographic composition of the respondents to provide insight into the sample distribution. Those demographic data are presented in pie charts, although the research design illustrates a qualitative approach. The data were collected from six respondents serving in safety academies and safety training centers. Each respondent held a different position: Senior HR Executive, Safety Manager, Training Manager, Managing Director, Deputy Health and Safety Manager, and Safety Officer. Regarding years of service, it was found that four members had five to ten years of experience in the safety training field, while the remaining two members had 20-25 years and over 25 years of exposure in the safety training field.

4. RESEARCH FINDINGS AND ANALYSIS

Data was collected from the six respondents using the semi structured interviews and their demographic data are as given in Table 1. These interviews were conducted to gather the opinions of industry experts, covering various aspects of the industry.

Table 1: Profiles of the interviewees

Code	CIDA Grading	Designation	Professional Experience (Years)
R1	C9 - Water Supply & Sewerage	Senior HR Executive	8
R2	C4 - Building Construction	Safety Manager	25
R3	C4 - Building Construction	Training Manager	7
R4	C5 - Building Construction	Managing Director	28
R5	C5 - Building Construction	Deputy Health and Safety Manager	10
R6	C6 - Building Construction	Safety Officer	6

For data analysis, both graphical and numerical methods were utilised. The analysis included examining the respondents' status, experience, education level, and more. Based on the data analysis and presentation, the respondents' names, safety institute or firm, and professional status were included in the personal profile and have not been taken into the research paper. The demographic composition of each individual response was then presented first to provide insight into their experience and sample distribution.

Based on Figure 1, most respondents had five to ten years of experience in the construction safety field, accounting for 66.67% of the total respondents. Additionally, an equal percentage of respondents, 16.67% each, had 20-25 years of experience and over 25 years of experience in the field.

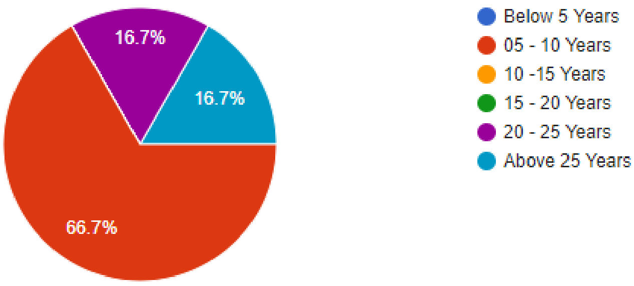

Figure 1: Experience in the safety field

In the Sri Lankan safety training field, there are main sources used for safety training programs. According to Figure 2, lectures and photographs/videos/presentations are mostly utilised, followed by team training and case studies. Game-based safety training methods are not widely used. Respondent R1 and R2 mentioned that; "in a country like Sri Lanka, traditional techniques are still popular since the non-availability of the hands-on experience".

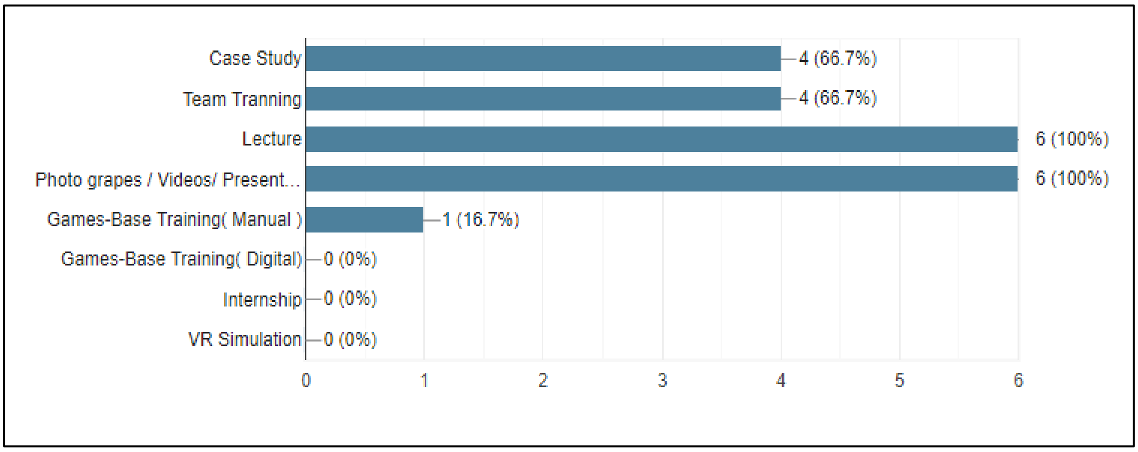

Figure 2: Sri Lankan safety training sources

According to Figures 3 and 4, VR technology is not being used in Sri Lanka for safety training.

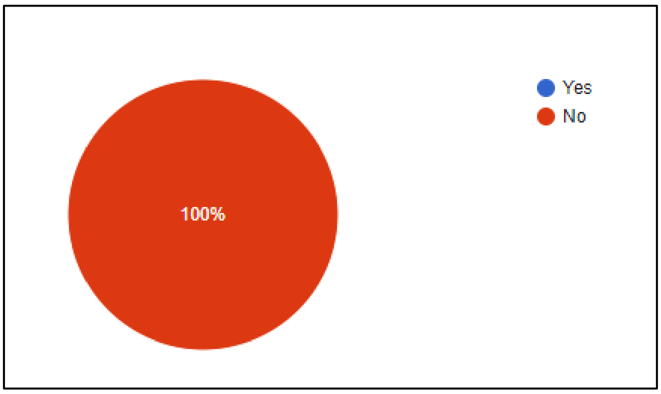

Figure 3: VR simulation safety training using in the construction field

In Sri Lanka, there are several reasons why VR technology has not been adopted in safety training programs, yet there is a potential for its expansion.

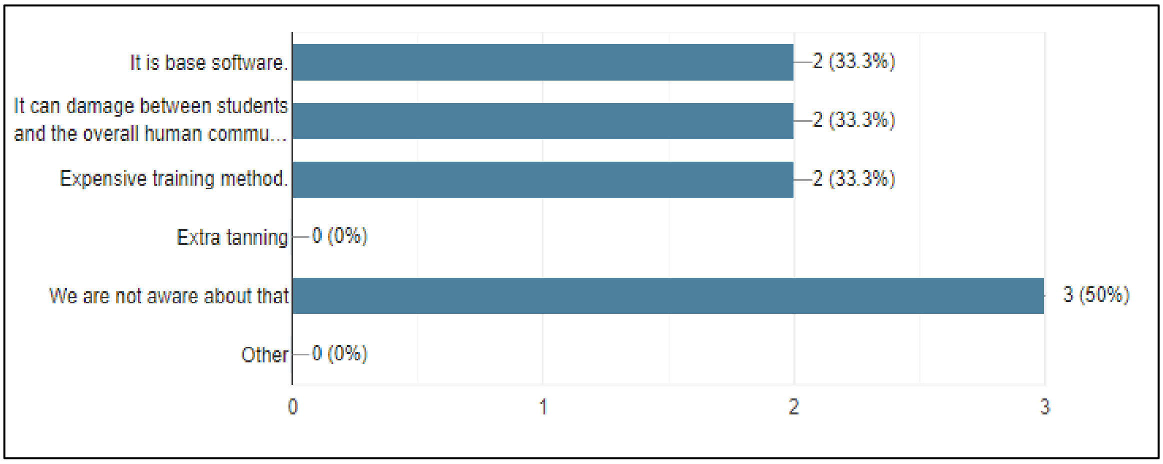

Figure 4: Reason for VR technology not involving the safety training program in Sri Lanka

As per the responses, 50% of the respondents were not aware of VR technology which is highlighted in Figure 5. Among the remaining respondents, 33.3% avoided using VR technology because they perceive it as an expensive training method, while another 33.3% avoided it due to concerns about potential damage to student interactions and overall human communication. Additionally, another 33.3% cited resistance to adoption due to its software nature.

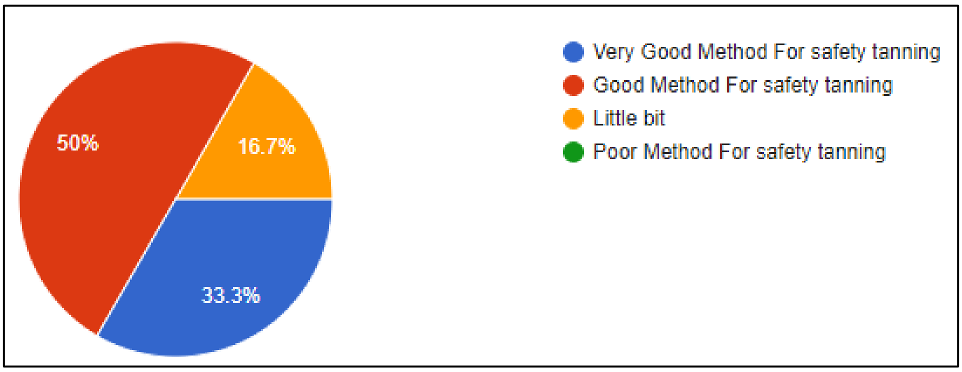

Figure 5: Respondent idea about VR technology

In accordance with the result, 33.3% of the respondents believed that VR simulator safety training is a very good method for safety training. However, the rest of the respondents had varying opinions, with 50% considering it as a good method and 16.7% viewing it as some kind of good software.

When using VR technology, workers can experience construction accident simulations in various situations. According to the responses represented in Figure 6, 33.3% strongly emphasised that VR simulation-based safety training can significantly improve safety skills in the workplace.

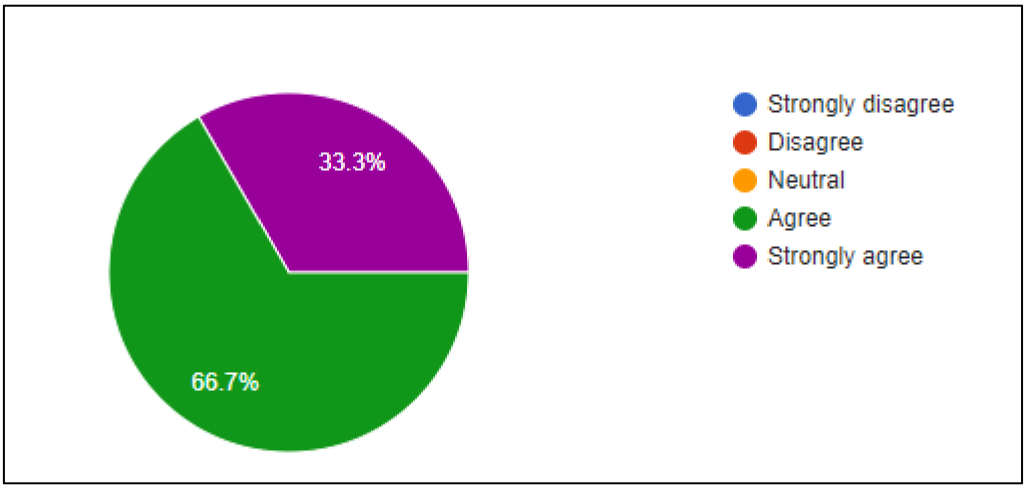

Figure 6: VR safety training improvement for the safety education

Responses strongly indicate that new trainees require virtual construction safety training before they begin their work. This sentiment is shared by 66.7% of respondents, with an additional 16.7% in agreement, as illustrated in Figure 7.

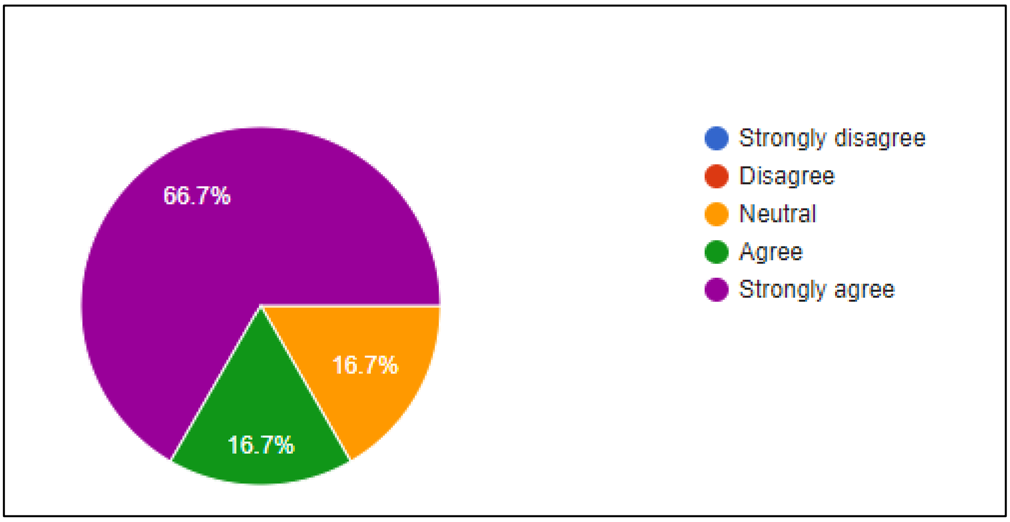

Figure 7: Important of the live-like safety training

In the construction industry, various types of accidents occur in day-to-day operations. Respondents believe that certain accidents need to be included in VR simulating construction safety training. According to the responses, 50% believe that VR safety training programs can effectively cover the construction accidents to mitigate unfair incidents. However, as shown in Figure 8, 16.7% of responses believed VR cannot be used for construction safety programs based on the mentioned accidents. Anyway, they have positive feedback regarding the use of VR as a tool for construction, particularly in the timely allocation of relevant resources.

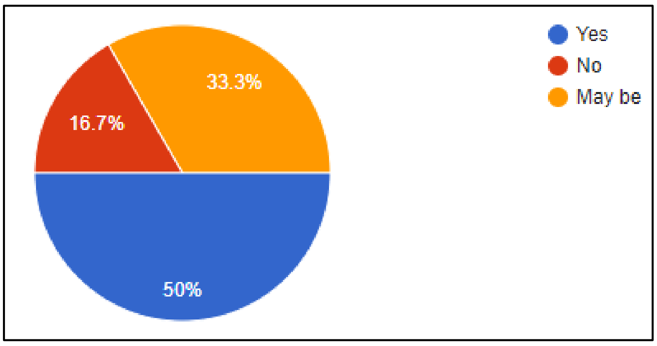

Figure 8: Response of the VR safety program.

5. CONCLUSIONS

The study investigated the potential of VR technology as a novel approach to safety training and accident prevention in the construction industry in Sri Lanka. The primary research objectives were to assess the effectiveness of VR in enhancing safety awareness and hazard recognition among construction workers, identify barriers preventing the adoption of VR technology in Sri Lanka, and propose strategies for integrating VR with traditional safety training methods.

Key findings from the empirical research and literature review revealed that VR technology offers significant advantages in safety training by providing immersive and realistic simulations of construction site scenarios. These simulations enhance workers' ability to recognise hazards and respond to emergencies effectively, which is not always achievable through traditional training methods. The qualitative data collected from interviews with industry experts highlighted that VR could significantly improve safety skills and emergency response preparedness among construction workers.

However, the study identified several barriers to the adoption of VR in Sri Lanka, including high costs, limited awareness and understanding of VR technology among stakeholders, and a lack of technical expertise and VR software developers. Additionally, concerns were raised about the potential negative impact of VR on interpersonal communication and interaction during training sessions. These barriers indicate a need for concerted efforts to promote and facilitate the adoption of VR technology in the construction industry.

To address these challenges, the study recommends increasing awareness and education about VR through workshops and seminars to educate stakeholders about the benefits and applications of VR technology in safety training. Financial investment and support from government bodies and private sector partnerships are crucial to subsidise the costs of VR equipment and software. Moreover, investing in the training of VR software developers and technicians is essential to build local expertise. Additionally, developing comprehensive training programs that combine VR simulations with traditional hands-on and classroom-based training can maximise engagement and effectiveness.

In conclusion, while VR technology presents promising opportunities for improving safety training in the Sri Lankan construction industry, its successful implementation requires overcoming significant barriers through targeted strategies. By addressing these challenges, the construction industry in Sri Lanka can harness the full potential of VR to enhance worker safety, reduce accidents, and improve overall productivity. The study solely focuses on the potential of VR implementation in the Sri Lankan construction industry. Therefore, it is recommended that future research explore the integration of VR technology with personal protective equipment. Additionally, investigating the effectiveness of VR technology implementation in other industries in Sri Lanka would be beneficial.

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