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Virtual Reality Training for Occupational Risk Prevention: Application Case in Geotechnical Drilling Works

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ABSTRACT

The construction industry is considered one of the most dangerous industries globally. The construction site is a complex environment where diverse teams of people interact with large machinery. In addition, the lack of safety culture on the job site and deficiencies in safety training increase these problems. Within the construction works, geotechnical drilling worksites involve high-powered machinery, and workers are exposed to different risks when using them. Despite these risks, safety training courses on these topics are not specialized. Most of the training courses are generic in occupational hazards, failing to address in detail the work dynamics and risks associated with geotechnical work, where heavy machinery is a fundamental factor. There is a lack of adequate learning content specific to drilling works, meaning the heavy machinery, how to use it and how to prevent accidents due to these drilling tasks are poorly understood. This research investigates the risks associated with geotechnical drilling work and explores the potential of virtual reality (VR) to simulate immersive work environments, focusing on interaction with drilling machinery. A geotechnical drilling machine modelled 3D and integrated into a realistic VR environment. The machinery motions and the different tasks of the work team were modelled. The simulation allows a worker to interact in a working environment, identify risks and prevent accidents, and, moreover, be trained in best practices for machinery usage, according to previous real-world experiences from senior workers.

1. INTRODUCTION

Architecture, engineering, and construction industry projects consider a series of stages, where different professionals and work teams interact at other time stages. This process is characterized by strong fragmentation, communication difficulties, and integration problems throughout the projects [1]. Geotechnical inspections and works are key in the early stages of projects in the construction sector. The use of heavy machinery characterizes this type of work. These machines operate at high pressures, exerting cyclic forces on the ground for aspects such as drilling, anchor placement and soil compaction, among others [2]. Although there is not a high number of workers at these stages, heavy machinery poses great risks for the operators [3].

Thus, while there may be few workers on the job site (close to where the geotechnical machines operate), accidents for workers interacting with the machine can be serious. In geo technical drilling works, the machinery can exert thrust forces of between 2 and 9 tons and rotational forces between 100 and 1200 rpm. These characteristics cause risks of accidents associated with: 1) hitting the machine head (this element moves vertically at low speed but with high forces and could hit a worker's head); 2) entrapment of clothing, hair, or a worker's limb by the rod; 3) crushing and/or blows from the rod, which can potentially break and fall from a height onto the worker; and 4) entrapment by machine jaws, which trap and hold the entire weight of the rod and can cause a worker's limb to be crushed [4].

The construction industry is one of the sectors with the highest accident rates [5]. This characteristic is associated with working conditions, safety management, and training methods [6]. The main objective sought by safety managers is to achieve a safety culture on the job site [7]. To achieve this goal, training in risk prevention is key. However, shortcomings in training have been identified [8, 9]. Theoretical or very general training plans fail to raise worker awareness of risk prevention issues. Another missing aspect is the lack of practical activities that bring the worker closer to real risk environments [10, 11].

The construction industry is currently in the process of digital transformation. Construction 4.0 has promoted incorporating elements of automation, digitization, and integration of the sector's processes. The digital tools and emerging technologies promoted by Construction 4.0 provide several advantages for construction operations (automation and digitization of design processes, tracking, and monitoring) and, in particular, worker and site safety [12]. In construction safety, standards promote health and safety management integration with building information modelling (BIM) environments. For example, PAS 1192-6:2018 addresses the collaborative sharing and use of structured Health and Safety information using BIM [13]; and ISO 19650:6 [14] (currently under development) includes a new section on safety and health within its topics of organization and digitization of information about buildings and civil engineering works, including BIM. These regulations create an enabling environment for incorporating these new ways of working. BIM and immersive technologies such as virtual reality (VR) and game engines provide new alternatives for innovation in training [15, 16]. Thus, based on BIM models of projects, it is possible to recreate a specific virtual scenario and provide it with activities and tools so that workers can interact in a virtual environment. Here, risk prevention training has great potential [17, 18]. It is now possible to recreate accidents or unsafe working conditions without putting the worker at risk, allowing possibilities to improve the shortcomings of current training methods used [19]. For geotechnical works, VR has been used mainly in training in the use of machinery, focusing on the functions, devices, and operation of these machines [20]. Thus, in these cases, the objective has been to train workers in a supervised virtual environment, considering safety aspects [21-23].

Considering the advantages of VR to support training processes in occupational risk prevention, together with the needs of the geotechnical sector to train their workers in the reduction of accidents in drilling machines [24, 25], this work: 1) develops a VR environment for training in accident prevention in geotechnical drilling works and 2) incorporates drilling machinery, operators, and simulates typical accidents in this type of work. The VR experience seeks to complement the traditional training currently used in this work, providing a tool that allows immersion and facilitates interaction and understanding of the processes and risks associated with these geotechnical activities. The application has been developed for initial use through computers, but with the potential for deployment on mobile devices or VR glasses.

2. RESEARCH METHOD

The Design Science Research Methodology (DSRM) has been used [26]. Figure 1 shows the research methodology, with four stages. **Stage 1-Identifying observed problems and motivations.** First, the risks associated with geotechnical drilling work were identified. Along with this, the training methods used in the industry, the problems presented by these methods and the trends regarding the use of VR for these training purposes were investigated. To collect this information, a literature review was conducted. The Scopus and Web of Science databases were used. In addition, risk prevention manuals and technical guides associated with these geotechnical works were incorporated. **Stage 2-Defining the objectives of a potential solution.** Second, based on the literature review analysis, the objective of a possible solution was established: how VR improves the risk prevention training processes associated with geotechnical drilling projects. **Stage 3-Design and development**. Third, a conceptual proposal for risk prevention training in geotechnical works was established. A virtual scenario and tools for immersion and interaction in the virtual environment were developed. **Stage 4-Demonstration**. Finally, the VR experience for drilling work was implemented. An evaluation and analysis of its practical usefulness were performed.

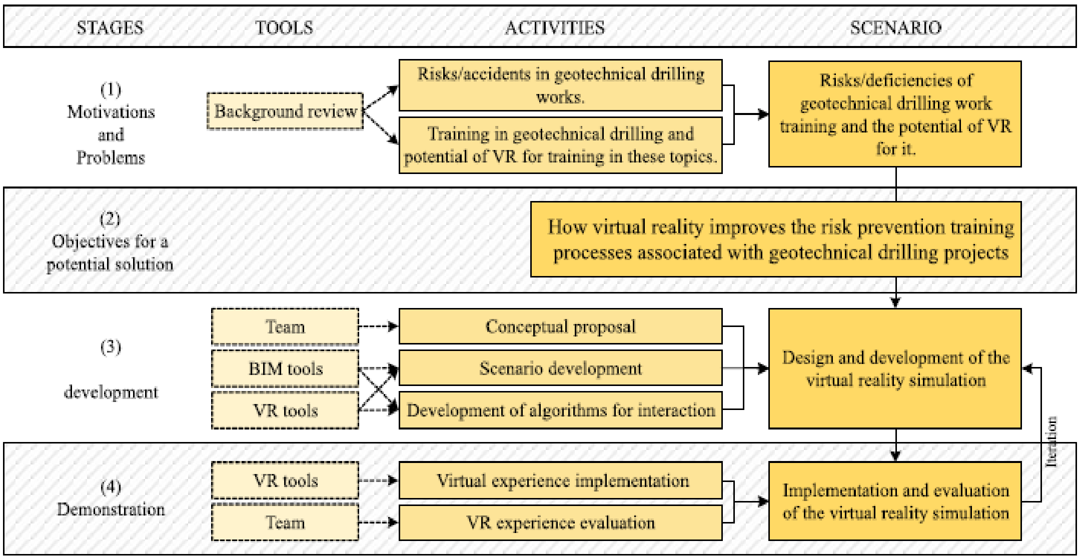

Figure 1. Research method

3. DESIGN AND DEVELOPMENT OF VIRTUAL EXPERIENCE

The virtual experience shows a geotechnical drilling work scenario. The objective of the experience is that the worker correctly performs the work of drilling and extracting soil coring, according to the instructions given by the drilling supervisor (virtual character). In this process, the worker must consider several safety aspects for the correct development of the work. The user will carry out his work normally (similar to the work in a real environment). While the worker performs his work, the virtual supervisor will indicate those actions that represent a risk and could lead to an accident. If the user suffers an accident in the virtual environment despite the recommendations, the virtual supervisor will recommend various actions to avoid these accidents and carry out the work successfully.

3.1 Design criteria

Several criteria have been considered in order to carry out the training experience. These are related to aspects of VR development and others from the technical perspective of geotechnical work and associated occupational hazards.

- **General training aspects**: Simulation should be seen as a training complement to traditional theoretical and face-to-face courses. The user to whom the simulation is addressed is considered familiar with the basic aspects of his or her work. In this way, it has also been considered that the user knows the usual working methodology and the necessary elements and tools. Under this criterion, we have worked on two important aspects whose presence on site must be indispensable: order and cleanliness in the work area and the correct way of lifting weights.
- **The realism of the scenario:** Creating a complete scenario has been considered, with all the elements of a real construction site context. Making the simulation as realistic as possible encourages immersion and concentration of the user. For this purpose, a construction site scenario must be created in an urban area, containing all the elements required in the work environment, such as signage and signposting of the work area, together with an environment surrounding the work area, with adjacent buildings, streets, vegetation, street furniture or vehicles, among others.
- **Realism of actions and animations**: The movements made by the drill and the helper (main character directed by the user) throughout the different drilling and extraction manoeuvres must be modelled. The user's actions consist of picking up the drill string and placing it correctly in the drill. The drill animations consist of the vertical movement of the drill head. The coordination between these actions and animations is very important to simulate the desired realism.
- **Risks**: the risks in geotechnical surveying associated with drilling rigs have been considered very important for the simulation design. In the geotechnical context studied, the main risks originate from the drilling machine. In this simulation, the risks represented were as follows:
  - Tripping: getting too close to certain elements placed around the stage causes the char- acter to fall. The user is notified that they have suffered a tripping accident, and it is explained to them that they must keep the work area clean to avoid it.
  - Hitting: getting too close to the drill head causes the character to fall. The user is notified that he/she has suffered a hitting accident, and it is explained to him/her that he/she should not get too close to the drill head, especially when it is moving.
  - Slamming: getting too close to the rear of the machine causes the character to fall. The user is notified that he/she has suffered a run of the accident, and it is explained to him/her that he/she should not stand in areas of poor visibility for the officer.
- **Gamification**: The simulation must be developed true to reality, but without the possibility of unforeseen drilling events such as breakdowns or blockages of drilling material in the ground, and a manoeuvre with full recovery must also be recreated. In addition, certain gamification tools are introduced. Gamification tools help maintain the user's interest and motivation in the simulation to prevent the simulation from becoming monotonous and boring. Thanks to these tools, the users need to stay and finish the simulation created. In this project, a series of instructions given by the secondary character must be implemented that are always visible so that the specific objective of the moment is not lost. These same instructions must introduce the final objective of the simulation, which is none other than to finish the survey and obtain the final sample witness without suffering an accident on the way. With these objectives always clear, final and specific, it is intended to keep the user attentive until they are achieved. Once achieved, the user should be notified that the work has been completed.
  A series of risks and accidents associated with each interaction must be added to motivate the user to carry out the actions without suffering the accidents. In the event of suffering.
- **Self-study:** This simulation should complement existing classroom-based courses. Therefore, its function transforms risks and accidents into a more immersive visual format. Throughout the simulation, the user is exposed to various risks and accidents that must be avoided. In case of an accident, the type of accident is notified, and information is given on avoiding it. These risks must be repeated several times so that the user has the possibility of correcting his mistakes if he has made them.
- **Standards perspective**: Development must be aligned with the standards associated with health and safety in construction and their integration with BIM. Because of this, normative references such as PAS 1192:6 [13] or the draft of ISO 19650:6 [14] provide an account of integrating safety aspects in the management with BIM models. Thus, the VR workflow must be linked to BIM models and management processes associated with safety control.

3.2 Design, workflow, and tools

The flow shown in Figure 2 describes the proposed design for the VR experience.

To capture the user's attention, the design considers a narrative and a cause-effect relationship tree associated with it. Thus, the user will be able to recognize the worksite and the actions to be performed there as if it were a real work sequence. In the first stage (main tab) are the instructions to be completed in the simulation, together with the controls for the different functions considered. The simulation starts with a request from the drilling professional (virtual character) for the user to follow a series of instructions to finish the job. The experience considers two processes: drilling and extraction.

In the extraction process, all the rods should be removed and the drilled sample (in the form of a hard rock core) recovered to be placed in boxes. The user must pick up the rods from the drill and place them on the trestles. The process of approaching the drill involves a risk of hitting the drill head. Finally, the rock core must be retrieved and deposited in the sample boxes; this action involves the potential risk of tripping over the boxes themselves. Figure 3 shows the sequence of actions to be performed to develop the VR experience.

In the first stage, technical information on the geotechnical drilling machine's operation, user manuals, and risks associated with its use are collected. This information makes it possible to recreate the virtual simulation as similar to reality as possible. As a result of this stage, the conceptual design of the simulation is created. In the second stage, a geotechnical drilling machine is modelled. It has been developed considering realism in terms of its appearance and accurate joints for realistic movement, selecting the level of detail as a balance between completeness and lightness of the application. In the third stage, a construction scenario is developed in the VR environment. The machinery has been incorporated as the main element. In addition, different user interactions to operate the machinery have been programmed, along with different sequences of possible user actions and interactions with the virtual environment. Finally, in the fourth stage, the virtual experience is compiled for the specific platform (PC, smartphone, and VR glasses). In this case study, the application has been developed for computer use. However, modifications could be made to adapt it to mobile devices and VR glasses. For this particular development process, the tools used included Autodesk Revit, Sketchup 3D, Unity 3D, and Visual Studio (C#).

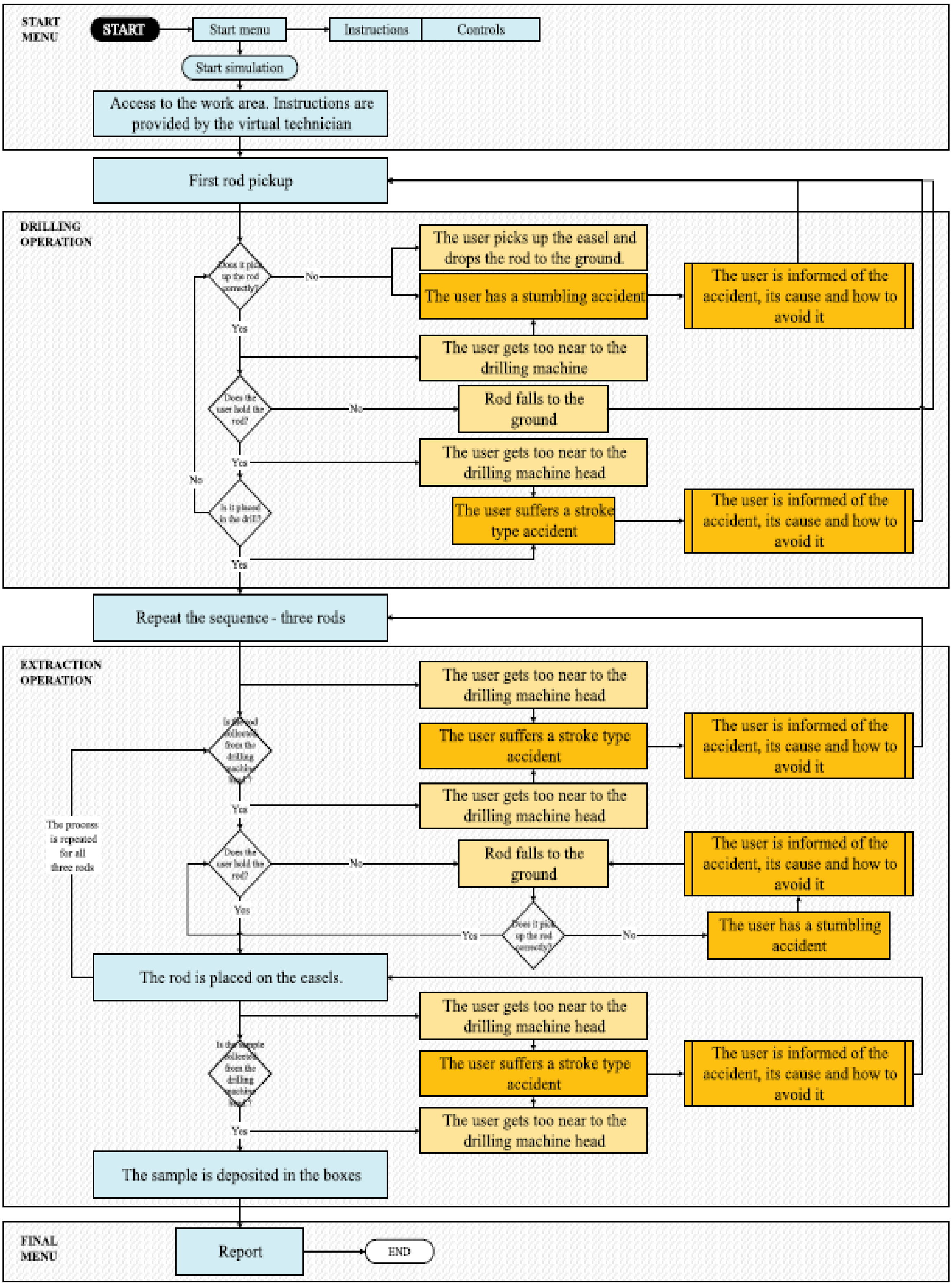

Figure 2. Conceptual design

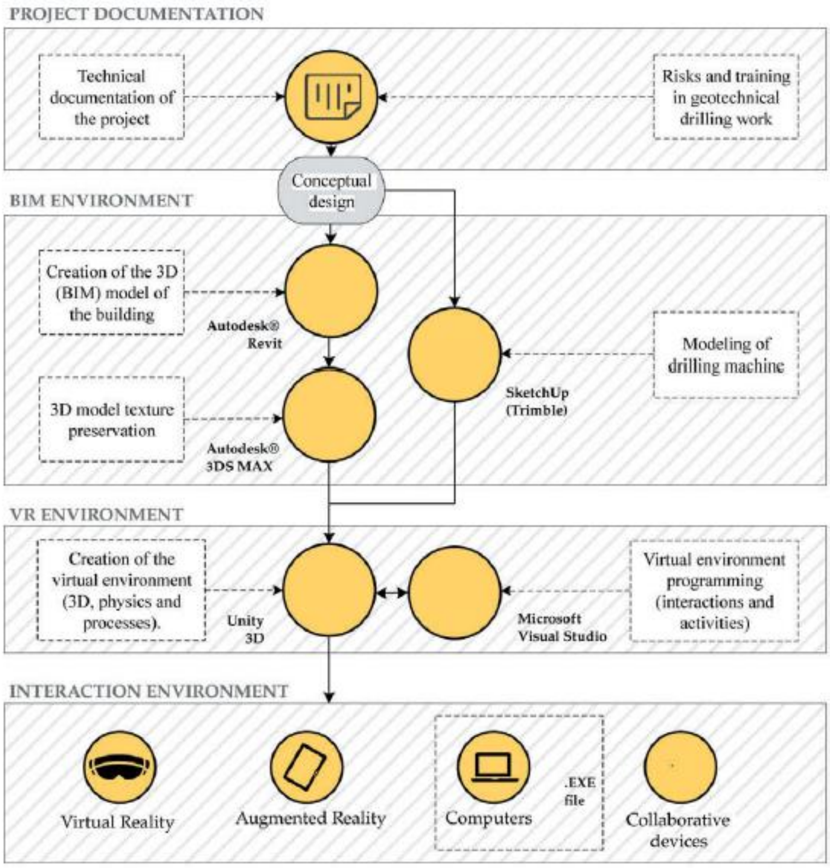

Figure 3. Workflow for the development of the experience

3.3 Modelling of geotechnical drilling machine

Figure 4 shows the 3D model of the geotechnical drilling machine developed for the simulation. Since the main objective of the experience is to train the worker in the correct use of the drilling machine, the work stages and associated risks, several elements have been considered to achieve realism in the model, both in the visual appearance and in the movements that it could perform in the virtual environment. Six parts of the machine have been considered: rotation head, penetrometer, rod assembly, control panel, clamps and retainers, and running gear. Table 1 shows the description of each part of the machine.

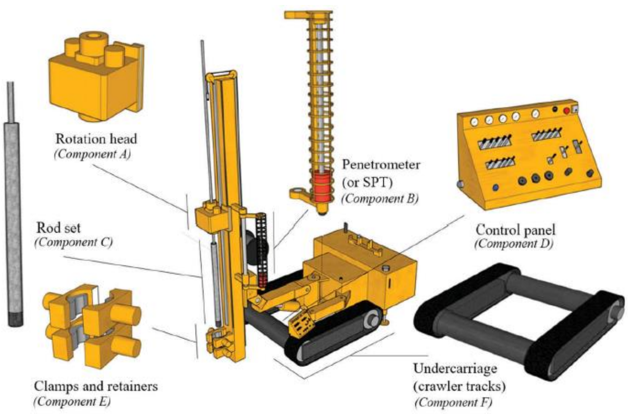

Figure 4. Drilling machine 3D model in Sketchup®

Another key element within the simulation is the scenario where the drilling machine is located. The virtual scene places the machine at the entrance of a construction site, surrounded by a realistic urban environment. Different zones have been established in the working area and possible user interaction zone. These zones are categorized according to their risk level for the user. Figure 5 shows the four interaction zones: the drilling zone (A, red); the control area (B, green); the rest of the perimeter of the drill (C, yellow); and work zone outside (D, blue). These delimitations of the different zones are not visible to the user; they only restrict the spaces to evaluate their behaviour (the display of the zones to the user could also be activated if desired). The four zones are as follows: **A. Drilling zone** (red) is the main working area located in front of the drilling machine. The operator in charge of supplying the machine and following the operator's instructions (assistant) carries out his work in this area. It is the main risk area as it contains all the moving parts of the drill while drilling. This area must be completely inaccessible to anyone outside the normal work team. **B. Control area** (green) contains the control panel that controls almost all the functions of the drilling machine; the driller is in charge of managing these controls and must remain in this area to ensure control of the machine at all times during drilling. **C. The rest of the perimeter of the drill** (yellow), the rear part and the part opposite the control area, is only frequented by the assistant if he/she needs access to the material storage drawers of the machine or a component such as the water pump. Even though the height of the drilling machines is not usually higher than that of a person, this area is considered to be of low visibility as the driller must always be attentive to the drilling area. For this reason, and even though the machine is considered static in working order, this area is included in the safety perimeter of the drill. **D. Work zone outside** (blue) the drilling area.

Table 1. Geotechnical drilling machine model components

N	Name component	Description
1	Rotation head	It is the part of the machine responsible for transmitting the rotation and thrust forces to the drill string, and therefore, to the drilled ground (*Component A, see Figure 4*).
2	Penetrometer	A mobile sub-component that allows execution of the stan- dard penetration test (SPT), sometimes also used for drilling (*Component B, see Figure 4*).
3	Rod assembly	Component composed of the drilling battery and the rest of the rod, which allows the transfer of forces from the rotat- ing head to the ground and extraction of the drilled sample (*Component C, see Figure 4*).
4	Control panel	Panel where each of the levers and regulators have been modelled, allowing their movement as necessary; these levers are responsible for driving almost all the functionality and movement of the machine. (*Component E, see Figure 4*).
5	Clamps and retainers	Each of the four pistons and their respective clamping pads were modelled independently, which allow the rod assembly to be held during the drilling and extraction process, as well as screwing and unscrewing the rod when necessary (*Component F, see Figure 4*).
6	Running gear	Made of rubber and modelled independently of the chassis, and reducer, present in the drilling machine to allow relative movement during displacement of the machine (Component G, see *Figure* 4).

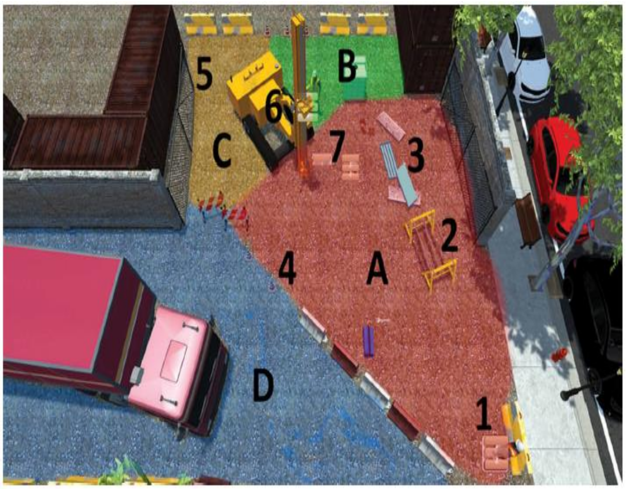

Figure 5. Work zones of the VR scenario

The working perimeter of the geotechnical drilling site is formed by zones A, B, and C. These constitute the risk zones, where only machine operators are allowed access. Figure 6 describes each interaction zone and details the sub-zones within each and the possible accidents within each. The geometry of the work zones and the accidents shown have been considered according to the particular machinery and worksite of this virtual experience. However, these features are simple to change, and the work zones will be adapted according to the specific construction site, the layout of the equipment or elements with which the user interacts, or the size or location of the drilling machine.

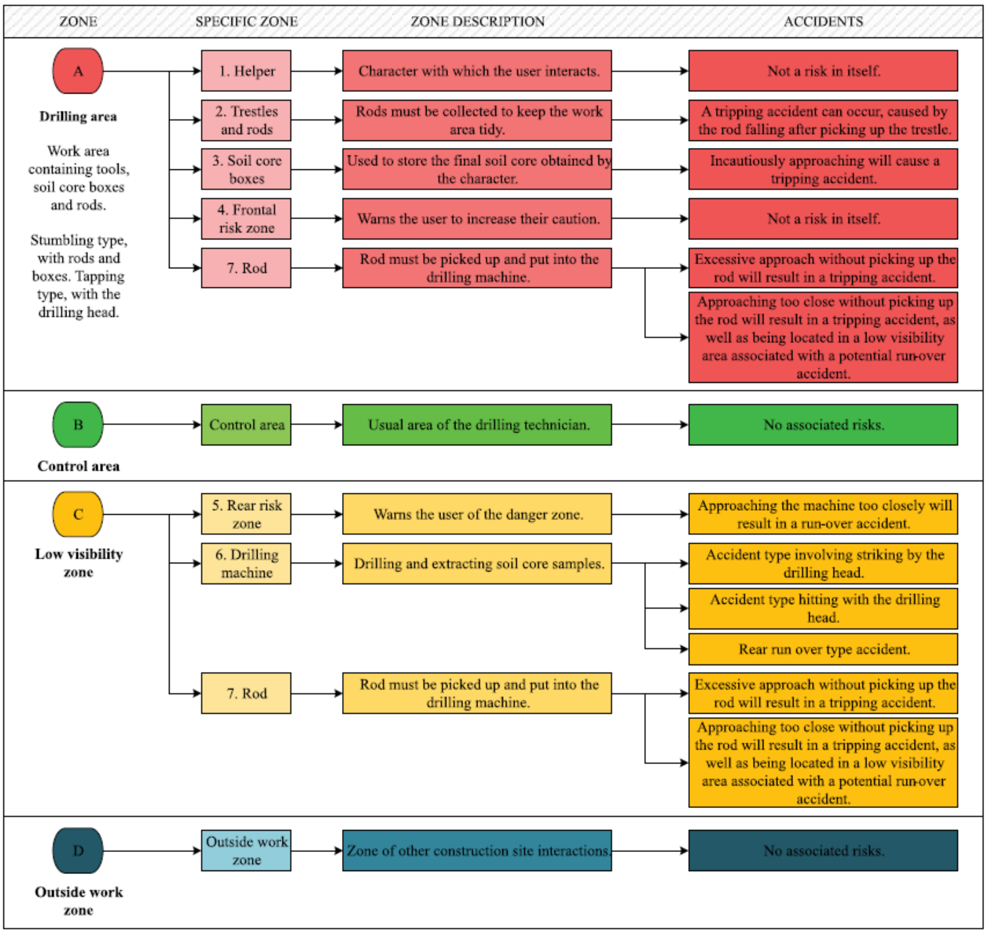

Figure 6. Zones and potential accidents

4. VIRTUAL EXPERIENCE

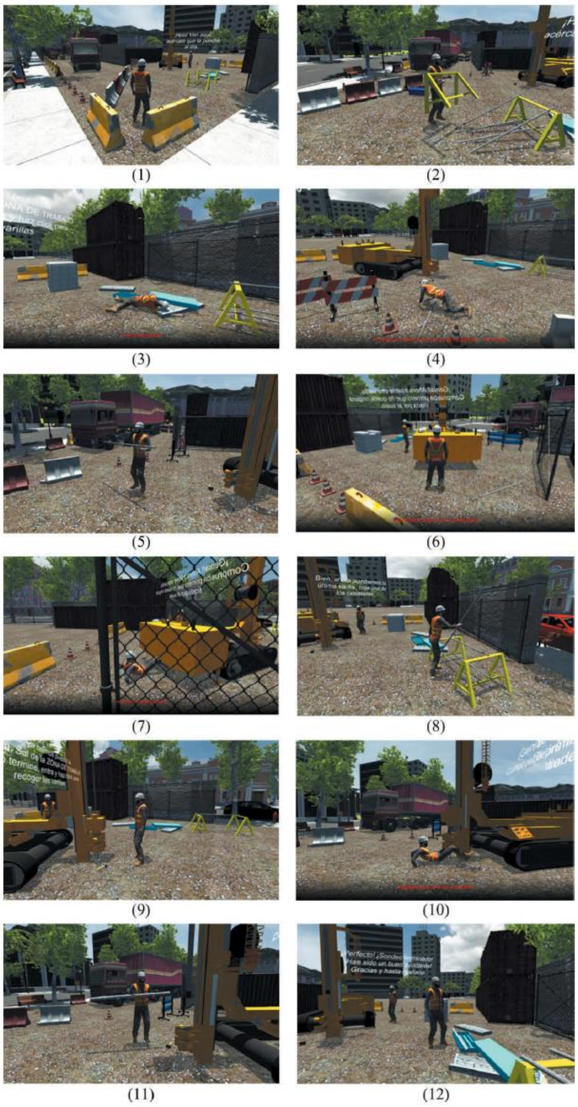

Figure 7. Scenes in virtual experience route. (1) Beginning of the simulation and drill operator's instructions, (2) lifting the trestle, (3) falling with the boxes, (4) falling with a rod, (5) lifting a rod, (6) rear area of the drill, (7) accident with the drill, (8) animation leaving a rod in the trestles, (9) rod extraction process, (10) accident with a drill head, (11) obtaining the rock core, and (12) completion message

Figure 7 shows the simulation sequence to illustrate the final result of the implementation and potential of the tool to train workers. Before starting the virtual experience, the worker must make the settings in the main menu and read the instructions for the correct execution of the simulation. Figure 7(1) shows the virtual worker (user) accessing the work zone. It is possible to see the construction site with all its components (machinery, protective equipment, and structures) and the context of the city. At this stage, the virtual supervisor gives the first instructions to the user to guide his actions within the work zone. After reviewing the instructions and the simulation operation in the start menu, the user enters the construction site. The worker will find the working area with the drilling rig and a drilling technician at the entrance. This virtual supervising technician will give instructions to the user throughout the simulation (Figure 7(1)). The user then has to prepare the machinery for a geotechnical drilling. This involves using all the elements arranged in the working area and the different equipment that make up the process. However, given that the virtual experience, together with training in the use of the machinery, has the objective of preventing accidents at work, different events may occur associated with this objective. For example, in Figure 7(2), a trestle has been picked up instead of a rod, causing the rod to fall to the ground.

In Figure 7(3) and 7(4), the user suffers tripping accidents; in the first one, by approaching and stepping on the storage boxes of the ground cores, and in the second one, by stepping on a rod. Before these accidents and others that may occur depending on the user's free behaviour, a message is projected at the bottom of the simulation screen, explaining the accident, the cause and the preventive measures to avoid its occurrence. In Figure 7(5), the user has correctly picked up the rod from the floor and is about to place it in the drill. On the other hand, Figure 7(6) and 7(7) show the sequence of a hit-and-run accident. According to the different work zones shown in Figure 5, the user is in an area of poor visibility. A message on the screen alerts him to this situation and that he is potentially in danger by remaining in that location. However, the user remains in the danger zone and moves closer to the drilling machine, resulting in an accident. He collides with the machine and suffers an accident, which is also notified by a message on the screen. Figure 7(8) shows the correctly executed action of depositing a rod on the trestles to keep the work area tidy.

On the other hand, Figure 7(9) and 7(10) show a run-over accident. It is possible to see the user close to the drill head, and after approaching, an accident when interacting with this area of the machine. Figure 7(11) and 7(12) show the user retrieving the last rock core from the bore- hole and placing it in the boxes; the final message from the driller notifying the user of the completion of the borehole is also shown.

An ideal working route where no accidents occur is visible after the end of the simulation. In this way, it is possible to compare the route the user has followed and compare it with the ideal and safe route. Since the user is free to perform various actions and move through the different zones of the virtual worksite, different alternatives and accident options can happen (up to a total of three different types, i.e., tripping, being run over, and being hit). The number of times and the order in which these accidents occur will depend on the user's decisions. In the case of such accidents, the user is informed and warned about how to avoid them in future. The simulation can also be started or terminated at any time.

5. ANALYSIS AND DISCUSSION

Geotechnical drilling works are dangerous. Accidents associated with these jobs are usually serious. Due to the power of the machinery and the actions it performs, accidents are typically quick, generally involving the loss of limbs. In this type of work, the worker's responsibility is high since incorrect machinery handling or standing in a dangerous area can cause an accident.

For this reason, simulations in immersion environments are of great help. The geotechnical drilling process considers from the time the machine is unloaded from the transport, placed at the point of the ground to be explored, the performance of drilling maneuvers, and at the end, the loading of the machinery for transport. Accidents can be recorded throughout the process. Therefore, the training must also consider this entire time spectrum. Accidents such as entrapment by the rotation of the drilling head, breakage and fall of rods from height, entrapment by the movement of the jaws, among others, can be incorporated. In addition, simulating other tests, such as an SPT striking test to add the risk caused by the striking mass of this tool, could be interesting for risk assessment and training of workers in risk prevention. Simulation can also incrementally incorporate several elements. From the technological perspective, developments applied to VR, augmented reality, or mixed reality experiences can be generated to find different channels to stimulate workers in work environments. On the other hand, from the perspective of learning methods, incorporating more gamification elements can improve the stimuli for workers and generate virtual simulations that encourage their use and the learning of these topics. In addition, from the perspective of storytelling, aspects of storytelling will strengthen the contexts of the simulations and develop non-linear experiences with multiple ramifications and bifurcations.

6. CONCLUSIONS

The construction sector has high accident rates. Within this sector, the geotechnical area contributes to these figures. The use of large machinery at high pressures implies different levels for operators and workers inside the worksite. Despite this, specialized training in occupational risk prevention in drilling activities is scarce. Moreover, traditional training uses passive teaching methods, which are far from the real conditions of the worksite. Therefore, there is a need to develop training experiences for geotechnical works using non-traditional teaching methods.

Information on the components and operation of geotechnical drilling machines was identified. Along with this, a work zone was established, along with the risks associated with each of the tasks in the geotechnical drilling process. With this information, a VR experience was developed. The implemented experience has considered three main aspects. First, a realistic construction environment, which feels like the construction site, the specific work areas with the drilling machinery, and a city environment, all with realistic aspects, to enhance user immersion. Second, a geotechnical drilling machine with realistic elements and movements which recreates the typical tasks of this type of machinery, facilitating user interaction and learning. Third, user interaction, actions, and consequences are associated with their different possible behaviours. Thus, the potential of VR tools for training has been demonstrated.

The adaptability and customization capabilities of these tools make it possible to generate scenarios and interactions according to users' needs. In the case of the construction sector, using BIM models in video game development environments optimizes the process of customizing and developing scenarios. To sum up, this research shows the conceptual and technological development of customized virtual training for geotechnical drilling works. The application is designed to be used before entering the construction site, or the construction site shed. A desktop application needs a controlled environment (such as the construction site). However, it could be adapted to mobile devices so workers can be trained anywhere. An extension of the application could be used through VR glasses to provide an immersive experience for the worker. As a future line of research, integrating Common Data Environments (CDE) with VR developments could provide a more sophisticated and accurate analysis of the worker's movement, identifying the worker's routes for each movement he/she makes. Regardless, software such as Revit and Unity offer alter- natives for analysing worker routes according to criteria or objectives of interest. It is interesting to study these automated routes and contrast them with the tendencies of workers in immersive contexts in order to evaluate the criteria of workers according to optimal work routes, safe routes, and the influence of various factors (work pressure, environmental factors, time, among others) that are of interest to study that influence the decisions of which route to choose.

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REFERENCES

[1] Muñoz-La Rivera, F., Vielma, J.C., Herrera, R.F., Gallardo, E. (2021). Waste identification in the operation of structural engineering companies (SEC) according to lean management. Sustainability, 13(8): 4249. https://doi.org/10.3390/su13084249

[2] Qian, Q., Lin, P. (2016). Safety risk management of underground engineering in China: Progress, challenges and strategies. Journal of Rock Mechanics and Geotechnical Engineering, 8(4): 423-442. https://doi.org/10.1016/j.jrmge.2016.04.001

[3] Luo, Z., Zeng, L., Pan, H., Hu, Q., Liang, B., Han, J. (2019). Research on construction safety risk assessment of new subway station close-attached undercrossing the existing operating station. Mathematical Problems in Engineering, Article ID: 3215219. https://doi.org/10.1155/2019/3215219

[4] Kale, Ö.A., Eskisar, T. (2018). Work-related injuries and fatalities in the geotechnical site works. Industrial health, 56(5): 394-406. https://doi.org/10.2486/indhealth.2017-0166

[5] Teizer, J. (2016). Right-time vs real-time pro-active construction safety and health system architecture. Construction Innovation, 16(3): 253–280. https://doi.org/10.1108/CI-10- 2015-0049

[6] Muñoz-La Rivera, F., Mora-Serrano, J., Oñate, E. (2021). Factors influencing safety on construction projects (FSCPs): types and categories. International Journal of

environmental research and public health, 18(20): 10884. https://doi.org/10.3390/ijerph182010884
[7] Zhou, W., Whyte, J., Sacks, R. (2012). Construction safety and digital design: A review. Automation in construction, 22: 102-111. https://doi.org/10.1016/j.autcon.2011.07.005
[8] Bruttini, A. (2018). Vito getuli pietro capone tommaso sorbi a project framework to introduce. Virtual Reality in Construction Health and Safety, 9, 166-175, 2018.
[9] Bhagwat, K., Kumar, P., Delhi, V.S.K. (2021). Usability of visualization platform-based safety training and assessment modules for engineering students and construction professionals. Journal of Civil Engineering Education, 147(2): 04020016. https://doi.org/10.1061/(asce)ei.2643-9115.0000034
[10] Kassem, M., Benomran, L., Teizer, J. (2017). Virtual environments for safety learning in construction and engineering: seeking evidence and identifying gaps for future research. Visualization in Engineering, 5: 1-15. https://doi.org/10.1186/s40327-017-0054-1
[11] Sunindijo, R.Y., Zou, P.X. (2013). Conceptualizing safety management in construction projects. Journal of Construction Engineering and Management, 139(9): 1144-1153. https://doi.org/10.1061/(asce)co.1943-7862.0000711
[12] Muñoz-La Rivera, F., Mora-Serrano, J., Valero, I., Oñate, E. (2021). Methodological-technological framework for Construction 4.0. Archives of Computational Methods in Engineering, 28: 689-711. https://doi.org/10.1007/s11831-020-09455-9
[13] (2018). British Standards Institution (BSI) Specification for collaborative sharing and use of structured Health and Safety information using BIM. 2018, 1-66.
[14] ISO/CD 19650-6 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM)-Information management using building information modelling-Part 6: Health and Safety Avail- able online: https://www.iso.org/standard/82705.html, accessed on Nov. 28, 2022.
[15] Mora-Serrano, J., Muñoz-La Rivera, F., Valero, I. (2021). Factors for the automation of the creation of virtual reality experiences to raise awareness of occupational hazards on construction sites. Electronics, 10(11): 1355. https://doi.org/10.3390/electronics10111355
[16] Li, X., Yi, W., Chi, H.L., Wang, X., Chan, A. P. (2018). A critical review of virtual and augmented reality (VR/AR) applications in construction safety. Automation in Construction, 86: 150-162. https://doi.org/10.1016/j.autcon.2017.11.003
[17] Xu, Z., Zheng, N. (2020). Incorporating virtual reality technology in safety training solution for construction site of urban cities. Sustainability, 13(1): 243. https://doi.org/10.3390/su13010243
[18] Young, A., Annereau, N., Butler, A. Smith, B. (2013). Case study: The leadenhall building, London. Int. J. Tall Build. Urban Habitat, 12-17.
[19] Lucena, A.F.E., Saffaro, F.A. (2022). Guidelines for exploring construction sites in virtual reality environments for hazard identification. International Journal of Occupational Safety and Ergonomics, 28(1): 86-95. https://doi.org/10.1080/10803548.2020.1728951
[20] Côté, S., Beaulieu, O. (2019). VR road and construction site safety conceptual modeling based on hand gestures. Frontiers in Robotics and AI, 6(15): 1-4. https://doi.org/10.3389/ frobt.2019.00015
[21] Kayhani, N., Taghaddos, H., Noghabaee, M., Hermann, U. (2019). Utilization of virtual real- ity visualizations on heavy mobile crane planning for modular construction. 2018 Proceedings of the 35th ISARC, Berlin, Germany, 1226-1230. https://doi.org/10.22260/isarc2018/0170
[22] Vahdatikhaki, F., El Ammari, K., Langroodi, A. K., Miller, S., Hammad, A., Doree, A. (2019). Beyond data visualization: A context-realistic construction equipment training simulators. Automation in Construction, 106: 102853. https://doi.org/10.1016/j.autcon.2019.102853
[23] Su, X., Dunston, P.S., Proctor, R.W., Wang, X. (2013). Influence of training schedule on development of perceptual–motor control skills for construction equipment operators in a virtual training system. Automation in Construction, 35: 439-447. https://doi.org/10.1016/j.autcon.2013.05.029
[24] Fernández, A., Muñoz-La Rivera, F.E.L.I.P.E., Mora-Serrano, J.A.V.I.E.R. (2022). Prevention of occupational risks in geotechnical drilling works through virtual reality training. Safety and Security Engineering IX, 206: 141-150. https://doi.org/10.2495/safe210121
[25] Muñoz-La Rivera, F.E.L.I.P.E., Mora-Serrano, J.A.V.I.E.R., Oñate, E. (2021). Virtual reality stories for construction training scenarios: The case of social distancing at the construction site. WIT Transactions on The Built Environment, 205: 37-47.. https://doi.org/10.2495/BIM210041
[26] Peffers, K., Tuunanen, T., Gengler, C. (2006). The design science research process: a model for producing and presenting information systems research. Software Engineering, 83-106. https://doi.org/10.48550/arXiv.2006.02763