PREVENTION OF OCCUPATIONAL RISKS IN GEOTECHNICAL DRILLING WORKS THROUGH VIRTUAL REALITY TRAINING

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ABSTRACT

The architecture, engineering, construction and operations industry has high accident rates as a result of characteristics of the construction site and work activities, the heavy machinery used and a lack of safety culture. In particular, geotechnical drilling worksites involve the use of high-powered machinery and workers are exposed to different risks when using them. However, risk prevention training courses are not well-specialised for this type of work. 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. Therefore, this research explores the potential of virtual reality technology as a tool for analysing the risks associated with geotechnical drilling works and as complementary training content to traditional courses. A specific use case, a geotechnical drilling machine is modelled in 3D and integrated into a realistic virtual reality environment where the movements of the machine are recreated, in addition to interactions so that workers can simulate the geotechnical drilling process, identify risks and prevent accidents, and, moreover, be trained in best practices for machinery usage, according to previous real-world experiences from senior workers.
Keywords: virtual reality, BIM, geotechnical drilling works, occupational risks, storytelling, construction site, training.

1 INTRODUCTION

Geotechnical works are an important element at the beginning of construction projects. Unlike the later stages of construction, where a large number of professionals, roles, and work packages interact at the site simultaneously, during the geotechnical work stages, the use of heavy machinery predominates. These machines operate at high pressures, exerting cyclic forces on the ground for aspects such as drilling, anchor placement and soil compaction, among others [1].

During this type of work, workers are continuously exposed to risks, where the misuse of machinery or carelessness in the workplace can cause accidents of varying degrees [2]. In drilling works, the machinery can exert thrust forces of between 2 and 9 tons and rotational forces between 100 and 1,200 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 [3].

High accident rates characterize the construction sector [4]. One of the most important aspects to help reduce these rates is training workers in occupational risk prevention. This process aims to create a culture of prevention through training that generates genuine awareness among workers [4]. However, training in accident prevention in construction has not been entirely effective, with deficiencies identified in both the content taught and the teaching–learning methods [5]. In the context of construction 4.0 and digitization trends in

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the construction industry aligned to building information modelling (BIM) [6], virtual reality (VR) and game engines provide successful alternatives to improve regular teaching of accident prevention in construction [7], by creating customised contents for each specific construction site, machinery to be used, tasks and profiles of the workers. In the field of geotechnics, virtual reality has been used to train workers in the handling of earthmoving machinery, the functions performed with these machines, and elements of accident prevention associated with their use [8]–[10].

Thus, considering the risks associated with geotechnical drilling works, the training needs and the possibilities offered by virtual training for these purposes, this study aims to create a virtual training environment to prevent occupational hazards in geotechnical drilling works. It contains a minimum work team, comprising a drilling machine and two operators, and recreates some of the most common accident types in these works. The simulation seeks to complement the current theoretical and digital training by providing an experience closer to reality thereby making it easier and more intuitive to apply the knowledge acquired through training to a real working environment.

2 RESEARCH METHODOLOGY

The Design Science Research Methodology (DSRM) has been adapted to guide the entire process of project justification, development and testing [11], with the following four stages: (1) identifying observed problems and motivations; (2) defining the objectives of a potential solution; (3) design and development; and (4) demonstration. Fig. 1 shows a diagram of the research methodology; in the first stage, a background review was carried out to identify the main risks involved in geotechnical drilling works, the types of training used and their deficiencies, in addition to how VR can improve the training. This literature search was conducted using the Scopus and Web of Science databases, together with handbooks and technical guides. In the second stage, the objective of a potential solution was defined: how the use of VR can help security training to geotechnical drilling works. In the third stage, the conceptual proposal was created, and the scenario and tools for virtual interaction were developed. Finally, in the fourth stage, the VR experience was implemented and evaluated.

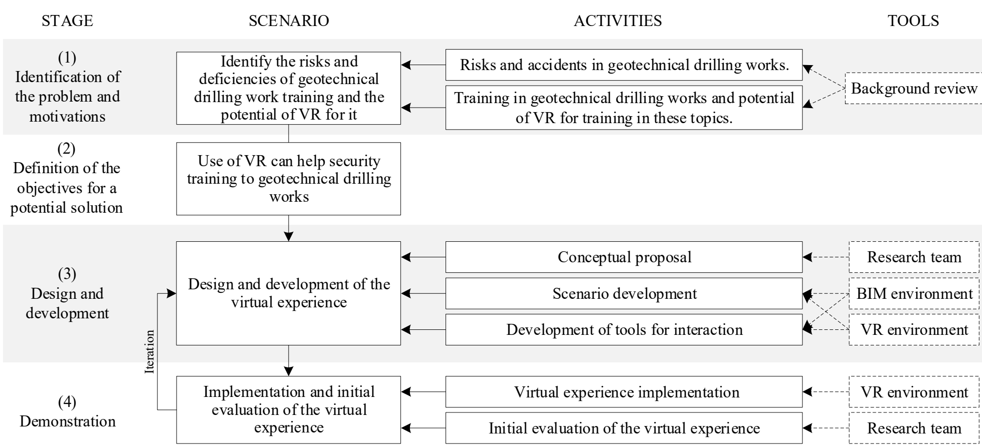

Figure 1: Research methodology.

3 DESIGN AND DEVELOPMENT OF THE VIRTUAL EXPERIENCE

The experience recreates a geotechnical drilling scenario. The user must perform the work of drilling and extracting soil cores, assisted by a virtual supervisor (driller) who will give the user the instructions of the process. The worker will then perform the process as they would in a real environment; however, the supervisor will warn of actions that could lead to an accident. In addition, if the worker suffers an accident in the virtual scenario, the supervisor will then provide recommendations to avoid the accident and perform the job.

3.1 Conceptual design, framework and tools for implementation

Fig. 2 shows the result of the conceptual design of the virtual experience, including the development of a narrative and related cause–effect relationship tree. In the initial main tab, the user will find the instructions and controls for how to use the simulation. At the beginning of the simulation, the driller then prompts the user to follow a series of instructions to finish drilling. The simulation is divided into two main processes: drilling and extraction.

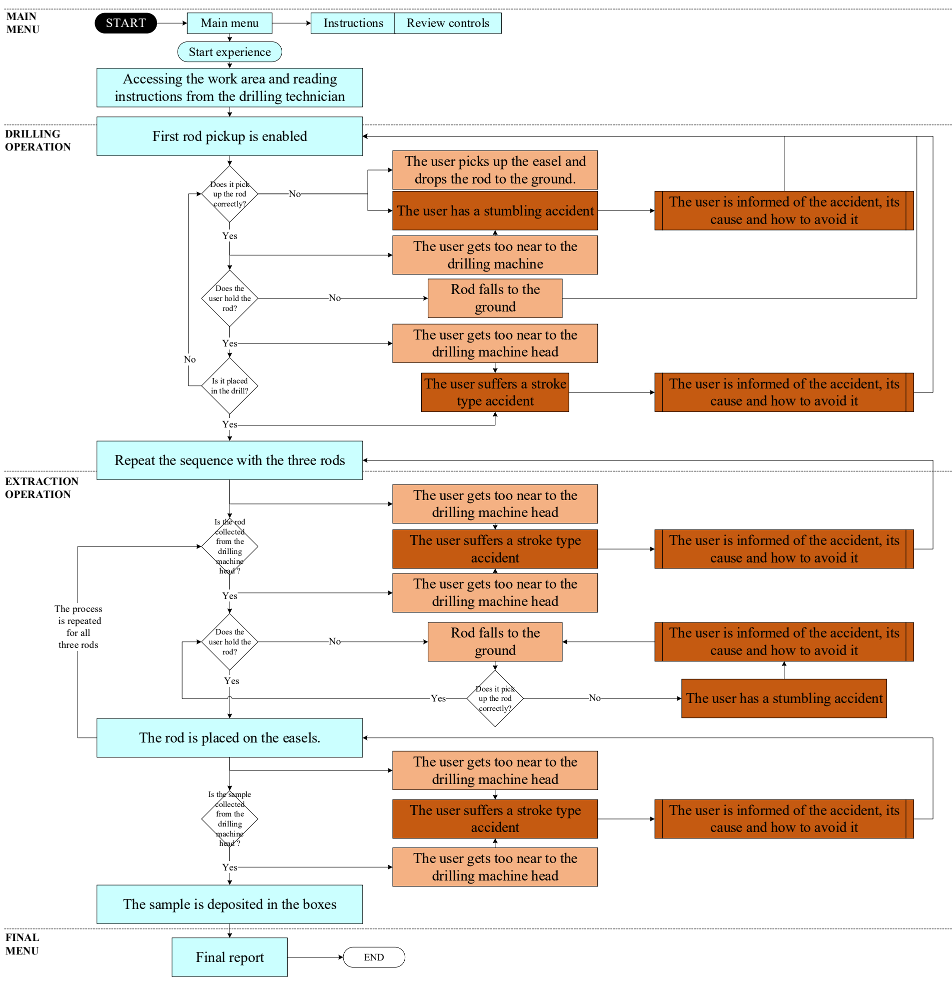

Figure 2: Conceptual design of the virtual experience.

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In the simulated drilling process, the user must search for and locate three rods, in the order indicated by the driller, strategically distributed around the working perimeter to finish placing them in the drill head. This could be changed depending on the kind of work the trainer would like to teach. Each rod has a potential trip hazard associated with it. In addition, rods two and three add a further associated risk; in locating the second one, there is the possibility of being run over by the machine. For the third rod, it is necessary to position oneself correctly so as not to catch the trestle instead of the rod, which would cause the rest of the rods to fall to the ground. In each instance when the user approaches to place the rods, they risk being hit by the machine head if they get too close. Then, 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.

Fig. 3 shows the steps to implementation of the VR experience. In step one, we obtained technical documentation of geotechnical drilling machinery uses and associated risks. Based on this information, the conceptual design shown in Fig. 2 is created. In step two, a drilling machine is modelled, 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 step three, a real construction scenario is generated in the VR development environment, incorporating that machinery, and programming the different user interactions to operate it, sequences of possible user actions and interactions with the virtual environment in general. Finally, in step four, the virtual experience is compiled for the specific platform (PC, smartphone, VR glasses). For this particular development process, the tools used included Autodesk Revit, Sketchup 3D, Unity 3D and Visual Studio (C#).

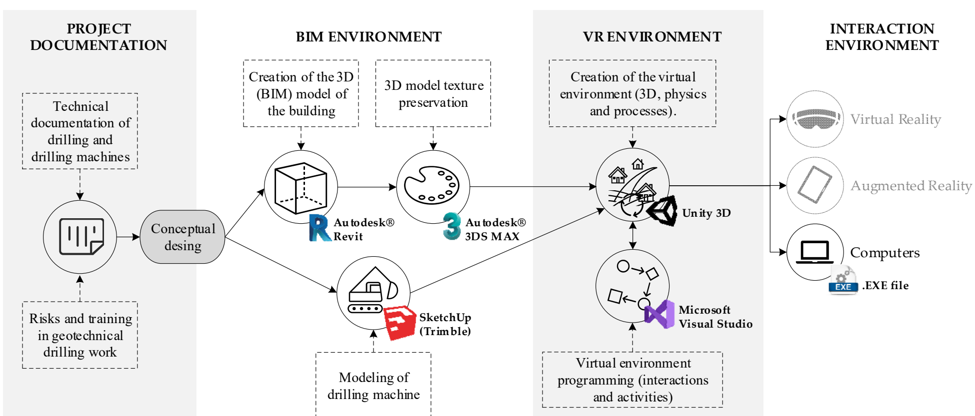


Figure 3: Workflow for creation of the virtual experience.

3.2 Drilling machine model

Since the main element of the training experience is the user's interaction with the drilling machine, a specific and typical drilling machine is modelled, as shown in Fig. 4. According to the objects defined for the virtual experience developed, several elements have not been considered. In this sense, with the objective of training in risk prevention associated with the use of machinery, six main parts of the model are highlighted and differentiated:

- Rotation head, responsible for transmitting the rotation and thrust forces to the drill string, and therefore, to the drilled ground.
- Penetrometer, a mobile sub-component that allows execution of the SPT (standard penetration test), sometimes also used for drilling.
- Rod assembly, composed of the drilling battery and the rest of the rod, which allows the transfer of forces from the rotating head to the ground and extraction of the drilled sample.
- Control 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.
- Clamps and retainers, where 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.
- 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.

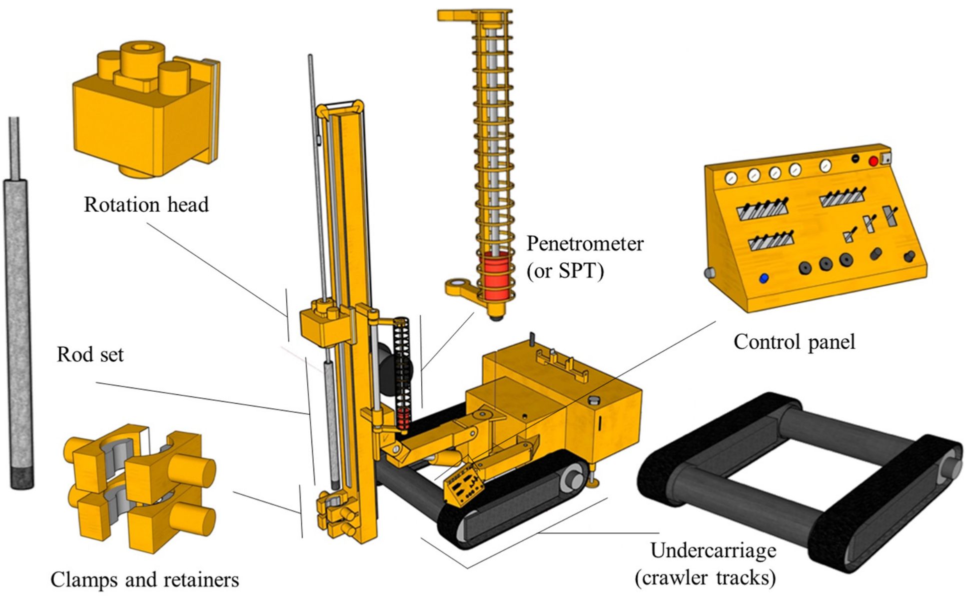
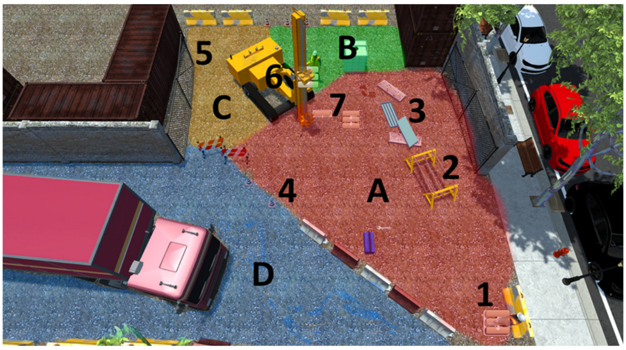


Figure 4: Drilling machine model in Sketchup®.

The second key virtual model is the construction scenario where the drilling machine is placed. In this case, different zones are marked depending on the risks (not visible to the user, but to code the different worker's interaction), as shown by the letters in Fig. 5(a), together with the environment of the construction site in Fig. 5(b)



(a)

(b)

Figure 5: Virtual scenario. (a) Work zones; and (b) General environment.

The four zones are as follows: (A) Drilling zone: located at the front of the drilling machine, this area is the main work zone of the assistant and should be the main attention zone of the driller; (B) Control area: this area 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. The rest of the perimeter of the drilling machine is only frequented by the assistant occasionally, including zone (C), i.e. the low visibility zone. This zone does not require continuous attention by the operators for this reason, and even though the machine is considered static when in working order, this zone is also included in the safety perimeter of the drill; (D) Work zone outside the drilling area. Zones A, B and C form the minimum safety perimeter where access is forbidden to any person except the drill site operators. Based on the zones shown in Fig. 5, Table 1 provides a description of each of these zones and the potential accidents associated with each of them, as considered in the simulation.

It is important to note that this classification can be easily modified and extended by the programmer and prevention technician, depending on the building site, kind of machinery and workers profile.

4 DEMONSTRATION OF THE VIRTUAL EXPERIENCE

Fig. 6 shows the simulation sequence to illustrate the final result of the implementation and potential of the tool to train workers.

After the typical settings and instructions from the main menu, the worker enters the work zone and receives instructions from the supervising driller (Fig. 6(a)). Three incorrectly performed user actions are then shown: in Fig. 6(b), a trestle has been picked up instead of a rod, causing the rod to fall to the ground and in Fig. 6(c) and 6(d), a tripping accident has occurred by approaching too close to the boxes and a rod respectively. In both accidents, a message is displayed at the bottom of the screen explaining what happened, the cause of the accident and how to avoid it. In Fig. 6(e), the user has correctly picked up the rod from the floor and is about to place it in the drill. Fig. 6(f) and 6(g) show the sequence of a hit-and-run accident, where the user is initially positioned in an area of poor visibility and is warned by a message in the lower area of the screen. In the latter image, the effect is shown of a user continuing to approach the drill until impacting with it, suffering an accident that is then notified on-screen. Fig. 6(h) shows the correctly executed action of depositing a rod on the trestles to keep the work area tidy. Fig. 6(i) and 6(j) show, once again, the sequence of a hit-

Table 1: Zones and potential accidents in virtual environments.

N	Name zone	Description	Associated accidents
A	Drilling area	Work area containing tools, soil core boxes and rods.	Stumbling type, with rods and boxes. Tapping type, with the drilling head.
B	Control area	Usual area of the drilling technician.	No associated risks.
C	Low visibility zone	Opposite to the helper and drilling technician, with respect to the drilling machine.	Contains a rod potentially liable to cause an accident due to low visibility.
D	Outside work zone	Zone of other construction site interactions.	No associated risks.
1	Helper	Character with which the user interacts.	Not a risk in itself.
2	Trestles and rods	Rods must be collected to keep the work area tidy.	A tripping accident can occur, caused by the rod falling after picking up the trestle.
3	Soil core boxes	Used to store the final soil core obtained by the character.	Incautiously approaching will cause a tripping accident.
4	Frontal risk zone	Warns the user to increase their caution.	Not a risk in itself.
5	Rear risk zone	Warns the user of the danger zone.	Approaching the machine too closely will result in a run-over accident.
6	Drilling machine	Drilling and extracting soil core samples.	Accident type involving striking by the drilling head.
			Accident type hitting with the drilling head.
			Rear run over type accident.
7	Rod	Rod must be picked up and put into the drilling machine.	Excessive approach without picking up the rod will result in a tripping accident.
	Rod	Rod must be picked up and put into the drilling machine.	Approaching too close without picking up the rod will result in a tripping accident, as well as being located in a low visibility area associated with a potential run-over accident.

and-run accident, in this case involving the drilling head. Fig. 6(k) and 6(l) show the user retrieving the last rock core from the borehole and placing it in the boxes; in addition, the final message from the driller notifying the user of completion of the borehole is also shown.

Once the user has completed the entire simulation, an ideal route can be viewed in which no accidents occur, and the one taken by the user. Notably, there are also alternative scenarios in which various accidents can occur, up to a total of three different types, i.e. tripping, being

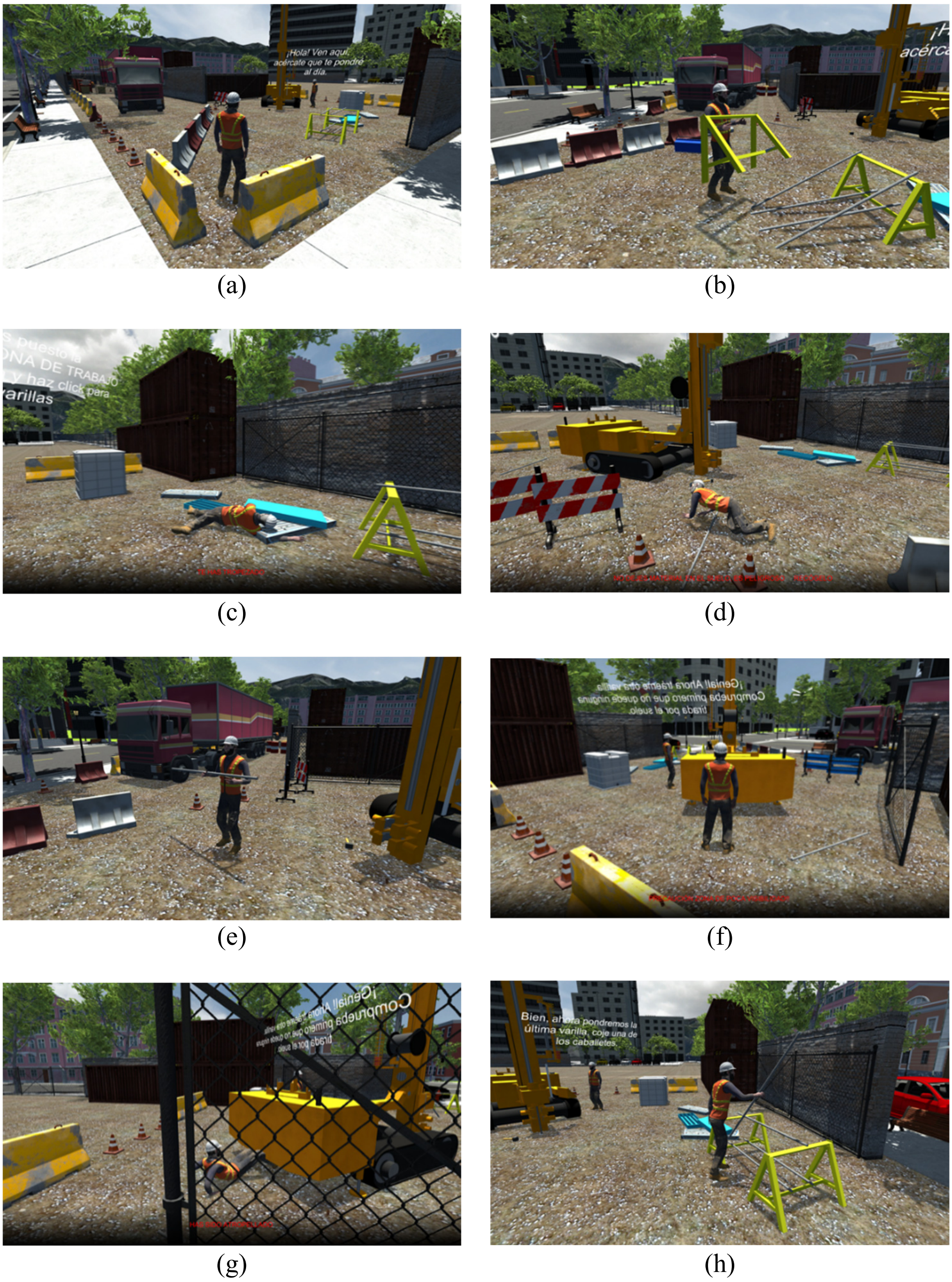
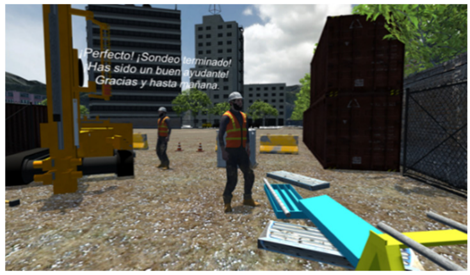


Figure 6: Scenes in virtual experience route. (a) Beginning of the simulation and drill operator's instructions; (b) Lifting the trestle; (c) Falling with the boxes; (d) Falling with a rod; (e) Lifting a rod; (f) Rear area of the drill; (g) Accident with the drill; (h) Animation leaving a rod in the trestles; (i) Rod extraction process; (j) Accident with a drill head; (k) Obtaining the rock core; and (l) Completion message.

(i)

(j)

(k)



(l)

Figure 6: Continued.

run over and being hit. 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 CONCLUSIONS

A virtual training experience for geotechnical drilling work was designed and implemented. Three relevant aspects are highlighted: the realism and functionality of the geotechnical drilling machine; the generation of a realistic work environment that allows realistic immersion; and the implementation of user interaction with designed actions and potential accidents. As a main conclusion, customised training criteria for the use of the machinery, cleanliness of the working area, accident prevention, and mastery of the work area are all considered. The potential for adapting virtual reality tools for training in diverse contexts and types of work in the construction sector has been demonstrated, thanks to the re-use of BIM models with multiplatform videogames platforms. To sum up, this research shows the conceptual and technological development of customised virtual training for geotechnical drilling works.

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