國立臺灣科技大學

NATIONAL TAIWAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

# CT5305701

# 計算機在營建管理上之應用

# Computer Applications in Construction Management

MidTerm VR Project Report

*VR Application Training for Construction Safety*

Submission Date: 17 October 2025

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# *VR Application Training for Construction Safety*

## 1. Introduction and Background

In this global era, the construction industry is one of the most dynamic and rapidly growing industries. This sector is the main pillar of economic development in various countries, not only creating physical infrastructure but also creating extensive job opportunities and driving growth in related sectors. However, the rapid development in the construction industry has not been accompanied by good construction safety standards, primarily due to a lack of education and understanding among workers. This presents a modern irony: on one hand, the industry is adopting advanced technologies like BIM, VR, AR, drones, and robotics, yet on the other hand, the most fundamental aspect Occupational Safety and Health (OSH) is often left behind.

According to World Risk Poll 2024 Report (Gallup, 2024) the construction sector consistently demonstrates a very high level of risk and injury globally. According to the data, 22% of construction workers worldwide have reported experiencing a serious injury at work within the past two years, positioning it as the second highest risk-industry after fishing (26%) as we can see in **Figure 1**. Workers in this field are routinely exposed to numerous hazards, including heavy machinery, outdoor work in various weather conditions, hazardous substances, and specific risk associated with working at heights and vehicle traffic on-site. The prevelance of injuries within the construction sector varies significantly based on demographic and regional factors. As shown in **Figure 2**, a distinct gender disparity exists, with 23% of male workers reporting injuries compared to 17% of female workers, indicating higher risk exposure for men, it indicates something bad where we know that the majority of construction workers are men. Furthermore, there is a strong correlation between a country’s income level and its injury rates; injury prevalances is highest in low-income countries at 28% where technology is rarely used and lowest in high-income countries at 11% where technology is common to use based on **Figure 3**.

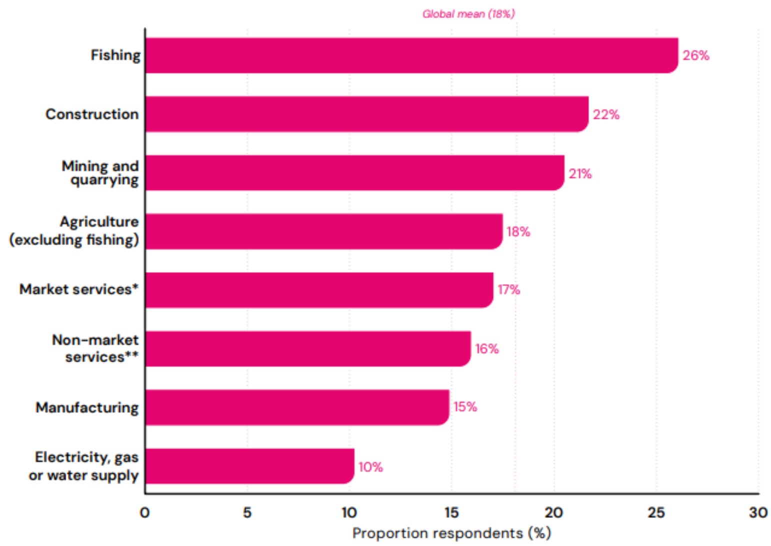


**Figure 1**: Percentage of Harm Experienced at Work by Global Industry

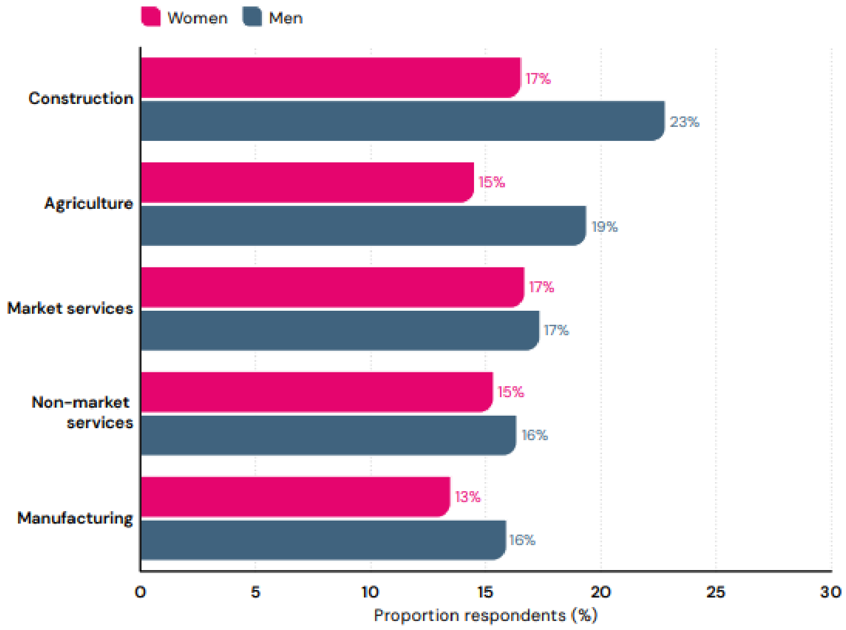


**Figure 2**: Percentage of Harm Experienced at Work by Global Industry and Gender

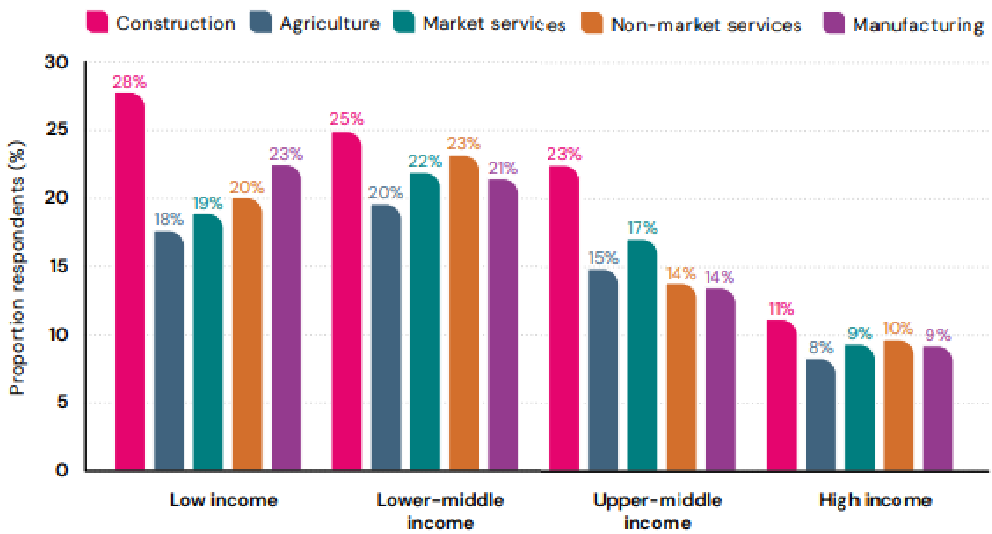


**Figure 3**: Percentage of Harm Experienced at Work by Global Industry and World Bank Country Income Level

However, the availabilty of OSH training remains a major global challenge for the construction sector, with significant disparities between regions. A majority of construction workers, 60%, have never received any OSH training based on **Figure 4**. This gap is highlighted by extreme regional differences: in Australia & New Zealand, where "white card" training is mandatory, 82% of workers have received recent training, wheres in North Africa, the percentage is only 6% as we can see in **Figure 5**. Interestingly, the report notes that despite this vast training gap, reported injury rates in both regions were surprisingly similar (9%), indicating that the effectiveness of training in reducing harm is complex issue influenced by multiple other factors.

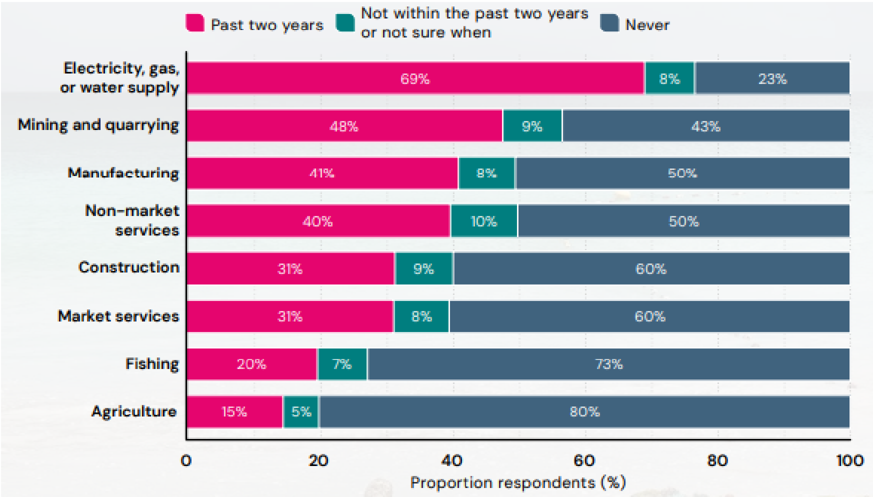


**Figure 4**: Percentage of OSH Training among Current Workforce by Global Industry

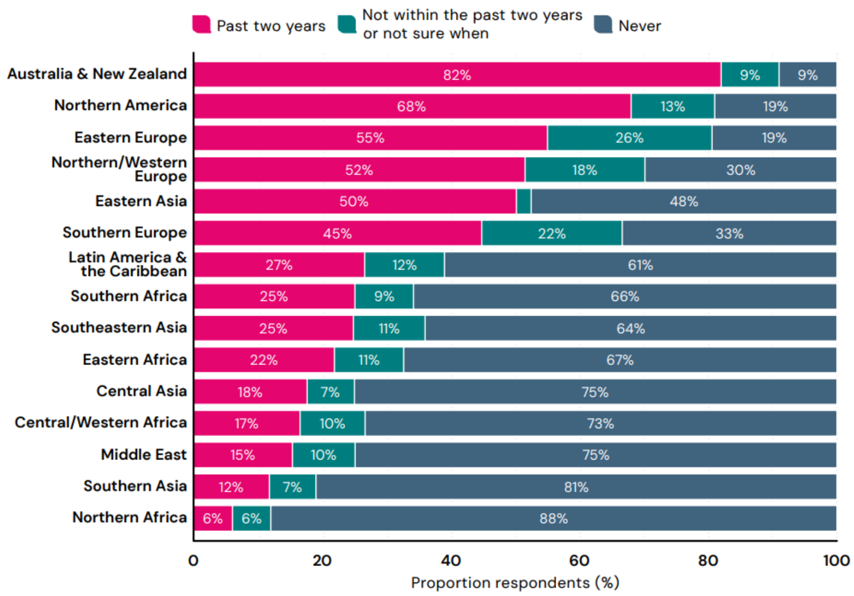


**Figure 5**: Percentage of OSH Training among Current Construction Workforce by Region

Data on OSH training in the construction industry above reveals that a significant number of workers have not received any safety training. Paradoxically, countries with high rates of OSH training still report workplace accident levels similar to those in countries with lower training rates. This suggests that the current implementation of OSH training may be ineffective. The majority of safety training worldwide continues to rely on traditional, less engaging methods, although a shift towards modern digital approaches like Virtual Reality (VR), Augmented Reality (AR), and Building Information Modeling (BIM) has begun. Virtual Reality is one of the method that we can use to simulate the OSH training for the construction industry, where the research by Man et al., (2024) shows that effectiveness of using VR was 0.593, 0.432, 0.777 higher than using the traditional methods. Its means that with the development and utilization of modern technology as OSH training will reduce the construction risk.

In this project, I will demonstrate how Virtual Reality (VR) technology is utilized to create an innovative and highly effective training platform for construction safety management. The core principle of this project is to leverage VR's unique ability to build an immersive, interactive, and entirely risk-free virtual environment that replicates a real construction site and the conditions. This allows workers to experience and learn from highly dangerous scenarios without facing any actual physical harm, bridging the critical gap between theoretical knowledge and practical, on-site application. Specifically, the VR implementation provides an immersive and safe environment to:

- Simulate unsafe scenarios and their consequences.
- Train workers to recognize hazards and adopt proper safety practices.
- Provide interactive feedback through visual and event-trigerred cues.
- Allow repetition and controlled experimentation without risking injury.

To demonstrate these capabilities, my project will focus on simulating three common high-risk scenarios:

- Mobile Crane Overturns Due to Missing Outriggers.
- Unsecured Materials Fall from Upper Floor.
- Worker Falls into a Void Due to Inattention.

Ultimately, this project will show that VR transforms safety training from a passive, lecture-based activity into an active, experiential learning process. By allowing workers to "feel" the consequences of safety violations in a controlled environment, the project aims to improve hazard recognition and safety compliance, with the final goal of reducing the number of preventable accidents on construction sites.

# 2. Objectives

The primary objectives of this VR Application for Construction Safety Training are as follows:

- To implement Virtual Reality (VR) technology in OSH training for construction safety.
- To simulate hazardous construction scenarios within a safe and controlled virtual environment.
- To enhance worker's hazard recognition skills and situational awareness.
- To demonstrate the critical outcomes of both adhering to and neglecting safety protocols.
- To improve training effectiveness and knowledge retention through an immersive, interactive experience.

# 3. Literature Review

The study by Sacks., et al. (2013) is a foundational piece of research that provided early empirical evidence for the advantages of using immersive VR in construction safety education. In their work, the authors developed and tested a VR training module, comparing its effectiveness against conventional slide-based training methods. Their finding were significant, revealing that the immersive VR environment led to superior knowledge retention and a deeper understanding of spatial risks on a construction site. The study highlighted that by allowing trainees to experience situations from a first-person perspective, VR training was particularly effective in creating lasting memoriess of hazards and correct procedures, establishing a strong case for its adoption over passive learning techniques.

Rokooei., et al. (2023) made a virtual reality application that was developed for the purpose of construction safety training, especially for roofing sector. The VR application was created using an agile development process that was directly informed by the input of the industry experts. To assess its effectiveness, a quantitative methodology was utilized for data analysis. The findings revealed that roofing professionals hold a positive perception of the application, vieweing it as a highly applicable supplementary training tool. Moreover, the research identified key influential factors that can guide the future design and development of other VR based safety training applications.

# 4. VR System Development and Implementation

## 4.1. Scene and Asset Preparation

### 4.1.1. Terrain and Environment Design

I created this virtual environment in Unity that we can see in **Figure 6** by utilizing its core features. First, I shaped the base topography using Paint Terrain tools to create the natural hilly areas and a flat section for the construction site area. Once the landform was complete, I used texture painting to coat the ground with various materials, such as a rock material for the steep cliff, a grass material for the hills, and a dirt or gravel material for the yard. Next, I placed various pre-made 3D assets (prefabs) to arrange a construction site area and a bridge to connect the road along the clifftop. As a final touch, I used the Paint Trees tool to add vegetation, populating the hills with trees to make the environment feel more alive and realistic. This main environment is designed to represent a hypothetical construction site.

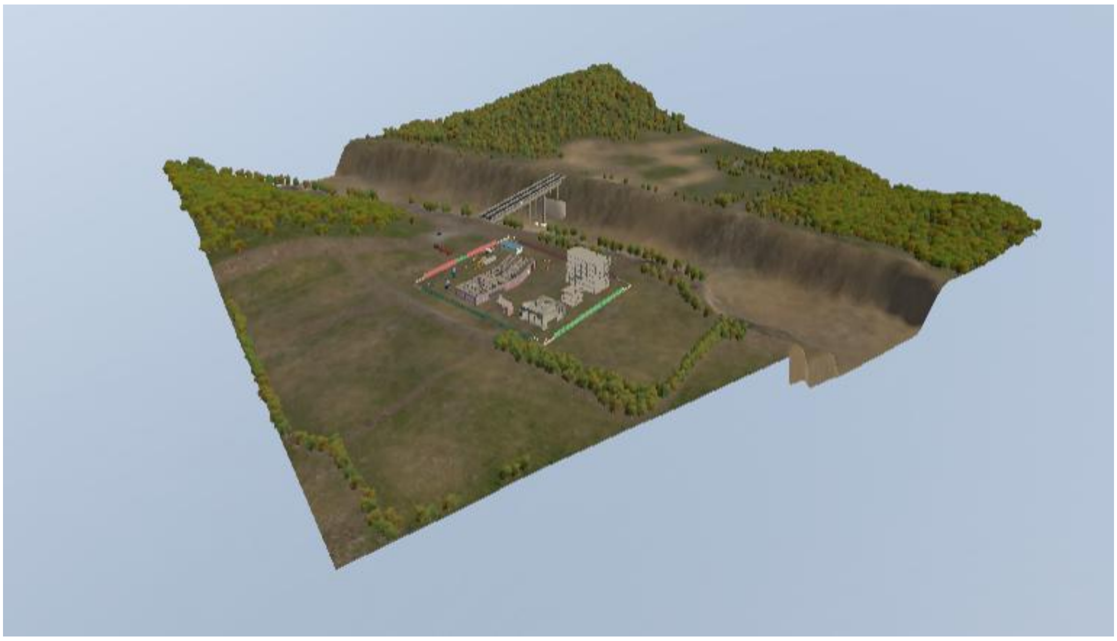

**Figure 6**: Terrain Used for The VR Application

### 4.1.2. Construction Site Area

The virtual environment for this project, shown in **Figure 7**, was designed as a fictional yet highly realistic construction site to ensure an authentic and immersive training experience. The scene is richly detailed with a variety of elements typically found in a real-world setting, which includes:

- Several partially completed building structures at various stages of completion.
- Animated workers engaged in activities, such as discussions and inspections.
- A range of heavy machinery, including a functional mobile crane and a concrete mixer truck.
- Key infrastructure like a main construction office, worker vehicles, and material storage areas.
- Various stockpiles of building materials, such as cements and steel beams.

All assets within the environment were built from high-quality 3D model prefabs acquired from various professional sources. These were then integrated, optimized, and arranged into a cohesive scene using the Unity game engine. A detailed breakdown of the objects used is provided in **Figures 8-13**.

**Figure 7**: Virtual Construction Site Area

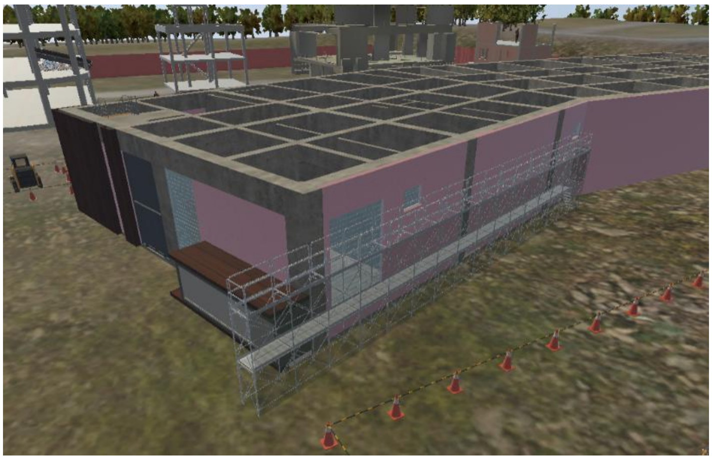

**Figure 8**: Detailed of Under Construction Structure (1)

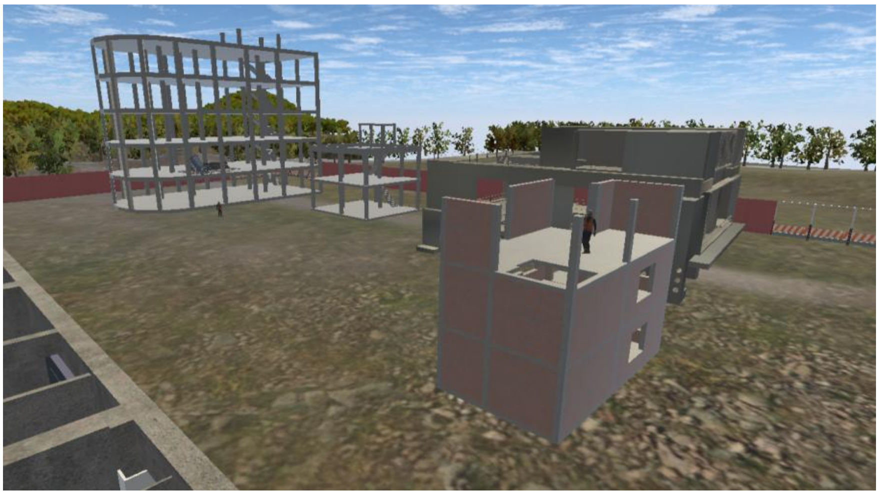

**Figure 9**: Detailed of Under Construction Structure (2)

**Figure 10**: Detailed of Construction Workers

**Figure 11**: Detailed of Heavy Machinery

**Figure 12**: Detailed of Construction Office and Worker's Car

**Figure 13**: Detailed of Construction Materials

#### 4.1.3. Construction Site Zone for Interactive Simulation

Within the main virtual construction site, three distinct zones were specifically designed to serve as the interactive stages for the safety training case scenes. Each area is dedicated to demonstrating a specific high-risk scenario, allowing the user to focus on a particular hazard:

- Crane Operation Area (**Figure 14**): This zone features a mobile crane and is set up to simulate an overturn incident caused by the failure to deploy outriggers, demonstrating a critical operational error.
- Multi-Story Structure (**Figure 15**): This area showcases an unfinished building where the scenario of unsecured materials falling from an upper level occurs, highlighting the importance of proper material handling and storage.

- Elevated Work Platform with Void (**Figure 16**): This scene contains an unprotected opening where a worker falls into a void due to inattention, a scenario designed to emphasize situational awareness and the necessity of guardrails.

**Figure 14**: Crane Operation Area

**Figure 15**: Multi-Story Structure

**Figure 16**: Elevated Work Platform with Void

#### 4.1.4. Character and Character's Animation Setup

- Worker characters are rigged and animated using Mixamo by Adobe like we can see in **Figure 17**.
- Character's animation includes walking, idle, talking, tripping, texting and walking, jumping, etc.
- Each Character's animation is assigned to the appropriate scenario using the Unity Animator Controller.

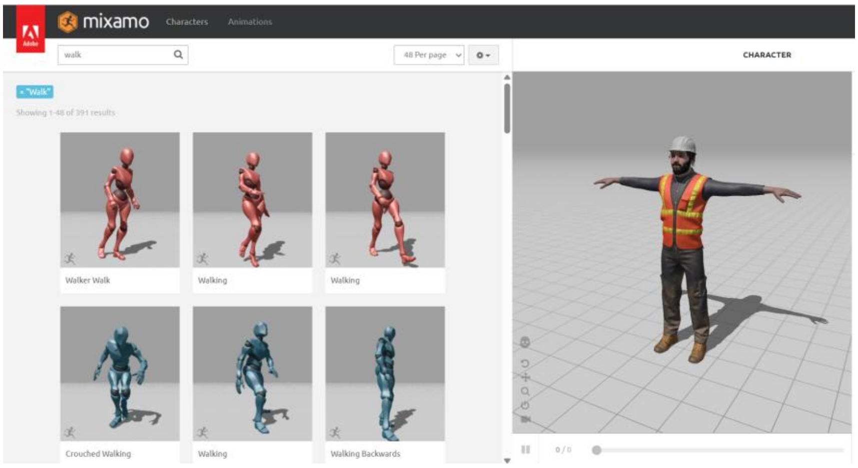


**Figure 17**: Mixamo by Adobe

## 4.2. VR System Development Process

#### 4.2.1. VR System Production Process

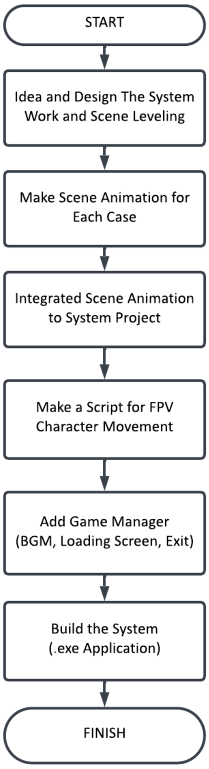


**Figure 18**: VR System Production Process Flow Diagram

**Figure 18** above illustrates the flowchart for the VR system's production process using Unity. The following sections provide a detailed explanation of each production stage and describe the core content and functionalities of the system:

- **Idea and Design The System Work and Scene Levelling**
  The core concept of this VR system is to provide a dual-mode training experience, combining free exploration with structured, guided scenarios. Workers are encouraged to freely explore the virtual construction site to familiarize themselves with the environment and identify potential hazards organically. The structured training itself is organized into several key parts:
  - A Welcome Scene: Upon first launching the application, the user is greeted in a dedicated welcome area. This scene functions as an orientation and tutorial, teaching the user the controls and objectives of the training before they proceed. The welcome scene will divided into three stage that user must read before start the training system, like we can see in **Figure 19**.


**Figure 19**: Three Stage/Level of Welcome Scene

  - Three Main Case Scenes: The primary training content is delivered through three distinct scenes, each focused on a specific safety hazard. Within each of these case scenes, the simulation unfolds through a four-stage, user-paced progression. Instead of being a passive video, the animation is divided into key stages. The user must provide input at each stage (for example, by clicking an “Play Animation" button to play the next part of the animation or “OK” to continue to next stage). This method ensures the user is actively engaged and controls the flow of information, allowing them to fully comprehend each step before moving on to the next. All of three scene is consist of this stage: Case Title, Unsafety Animation Condition, Prevention Animation, and Safety Animation Condition, where before the stage start, we also must click the arrow that located in several places in construction site area to begin involve in the selected scene like in **Figure 20**. User can randomly select where scene they want to start first and there is no sequence of scenes to follow. The stage/level for each scene can seen in **Figure 21-23** (The images are arranged in reading order: starting from the top-left, moving to the top-right, followed by the bottom-left, and finally the bottom-right).

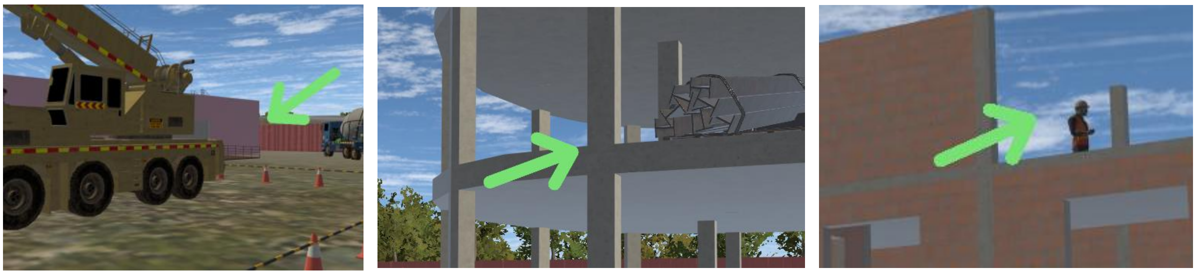

**Figure 20**: Arrow to Start Each Case Scene Stage/Level Scenario

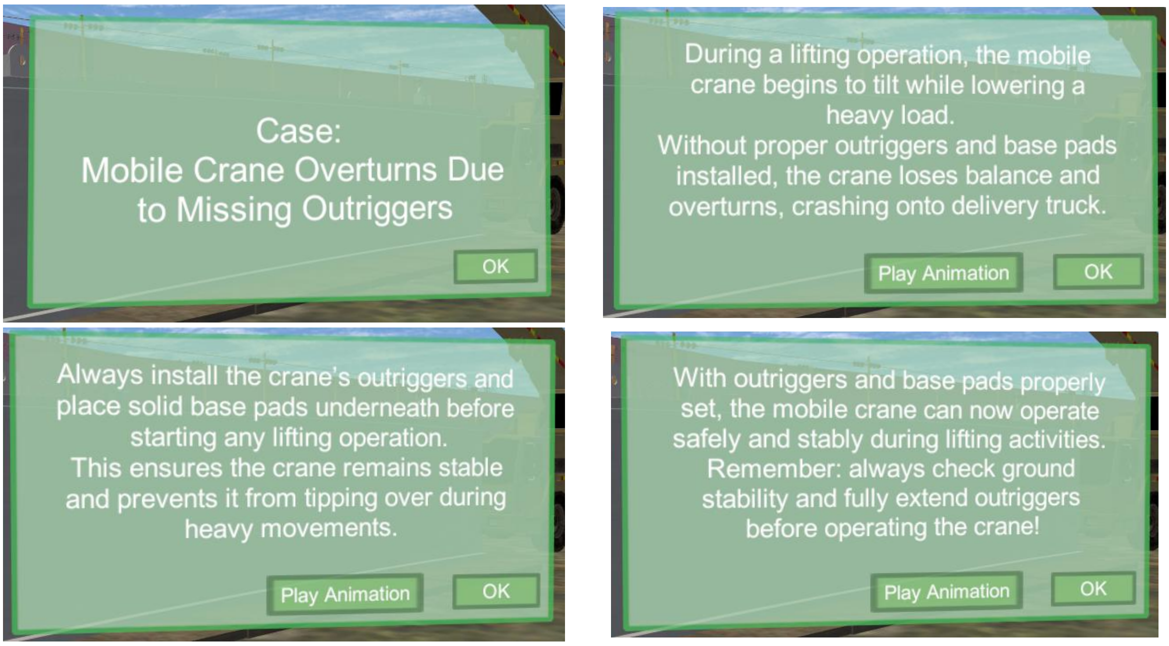


**Figure 21**: Four Stage/Level of Mobile Crane Overturns Due to Missing Outriggers Case.

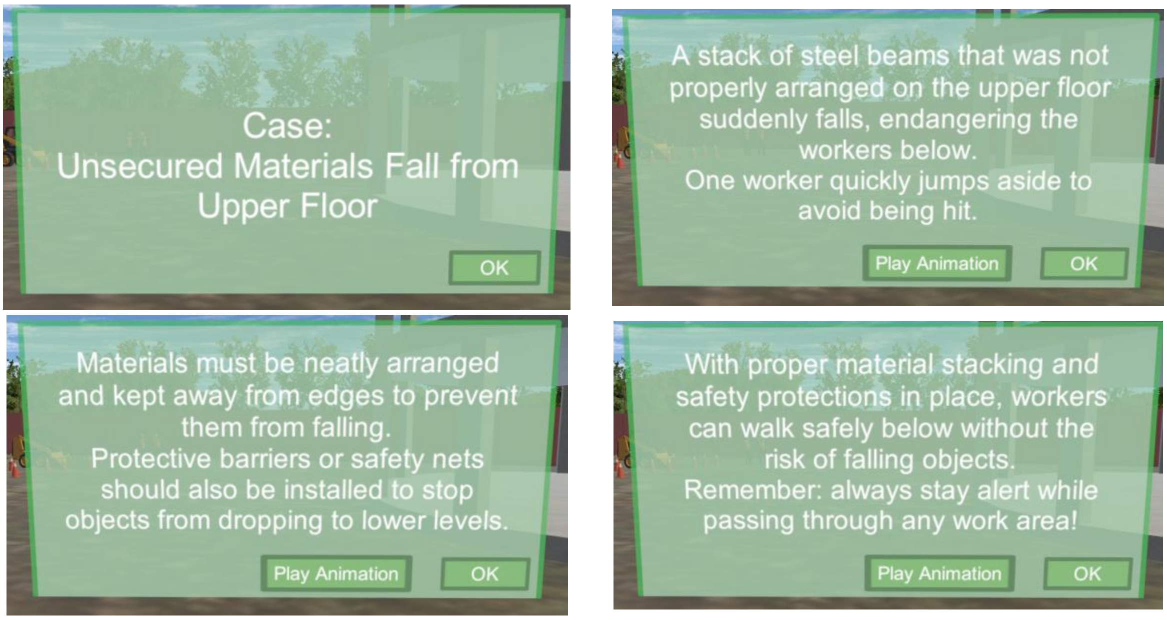


**Figure 22**: Four Stage/Level of Unsecured Materials Fall from Upper Floor Case.

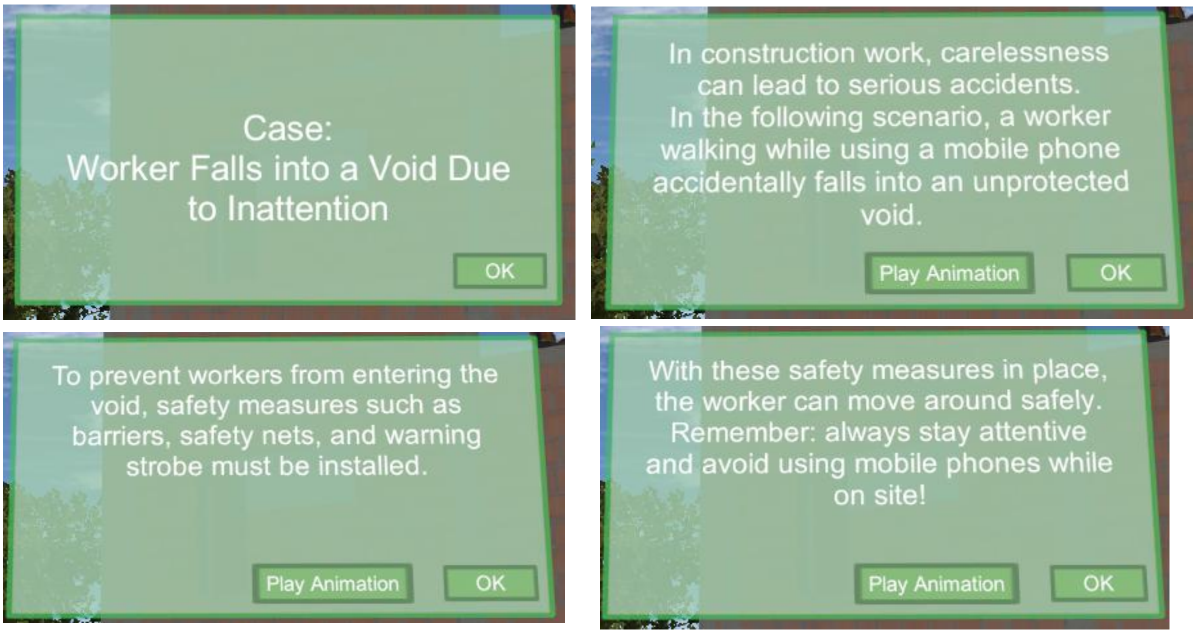


**Figure 23**: Four Stage/Level of Worker Falls into a Void Due to Inattention Case

- **Make Scene Animation for Each Case**
  For each case scene, a specific sequence of animations was developed to align with the previously described stage-based progression. This sequence is broken down into three key phases: the Unsafe Condition Animation, the Prevention Animation, and the Safe Condition Animation. In addition to these core scenario animations, looping "ambient" animations of workers conversing were also integrated throughout the site. The purpose of these background animations is to populate the environment, ensuring the construction area feels dynamic and alive, rather than static and empty, from the moment the application starts. **Figure 24** shows the Animation window within Unity, illustrating where these animation clips were created and sequenced. These animation involves rotating, moving position, scaling for both parent and child object.

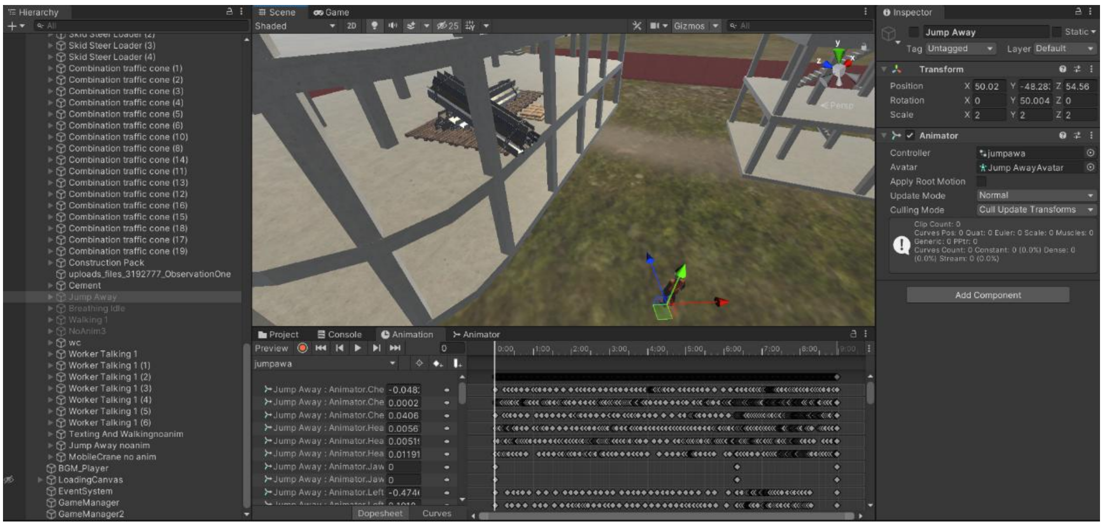

**Figure 24**: Animation Window in Unity to Make The Animation

- **Integrated Scene Animation for System Project**
  The animation clips created for each scenario were then integrated into their respective scenes to build the interactive training system. This process was managed primarily using Unity's Animator Controller, which acts as a state machine to govern the animation flow according to the user's progression. Each key animation (e.g., Unsafe Condition, Prevention, Safe Condition) was assigned to a distinct Animator State. To ensure a seamless and smooth experience without animations overlapping incorrectly, Transitions were carefully configured between these states. These transitions were given a blend duration to create a smooth cross-fade effect rather than an abrupt cut. User control was implemented by linking UI events to this state machine. At each stage of the progression, a "VR UI Button" is presented to the user. When clicked, this button's OnClick() event triggers a script (such as a "Simple Active" script) which in turn sets a parameter or trigger in the Animator Controller. This action prompts the state machine to transition to the next animation clip, effectively allowing the user to control the pace of the training narrative.

- **Make a Script for FPV Character Movement**
  In this stage, a first-person view (FPV) character controller system was implemented to enable navigation within the virtual environment. This system is crucial for allowing the user (or the developer during testing) to move around and freely explore the construction site as if they were a character within it. The core of this functionality is a custom C# script designed to perform two primary functions:
  - Movement Logic: The script reads input from the keyboard (e.g., the WASD keys) and translates it into movement commands. This movement is then applied to Unity's CharacterController component, which handles basic physics such as collision detection with other objects in the environment.
  - Look Logic: The script also reads input from the mouse to control the view rotation. Horizontal movement (left and right) rotates the entire character body, while vertical movement (up and down) rotates the camera within a limited angle to prevent unrealistic flipping of the view.

- **Add Game Manager (BGM, Loading Screen, Exit)**
  To enhance the overall user experience and provide essential application-level controls, a set of core systems was implemented. This stage focused on three key features: background music, a loading screen, and an exit function.
  - Background Music (BGM): Royalty-free background music was integrated into the application. The BGM plays continuously to create a more immersive and less silent atmosphere, making the virtual environment feel more dynamic and engaging for the user.

- Loading Screen: A loading screen was developed to provide a polished transition when the application first starts. This screen is displayed for a brief, set duration upon launch, which effectively masks any background initialization processes. Once this period is over, the loading screen disappears, smoothly revealing the main virtual environment to the user.

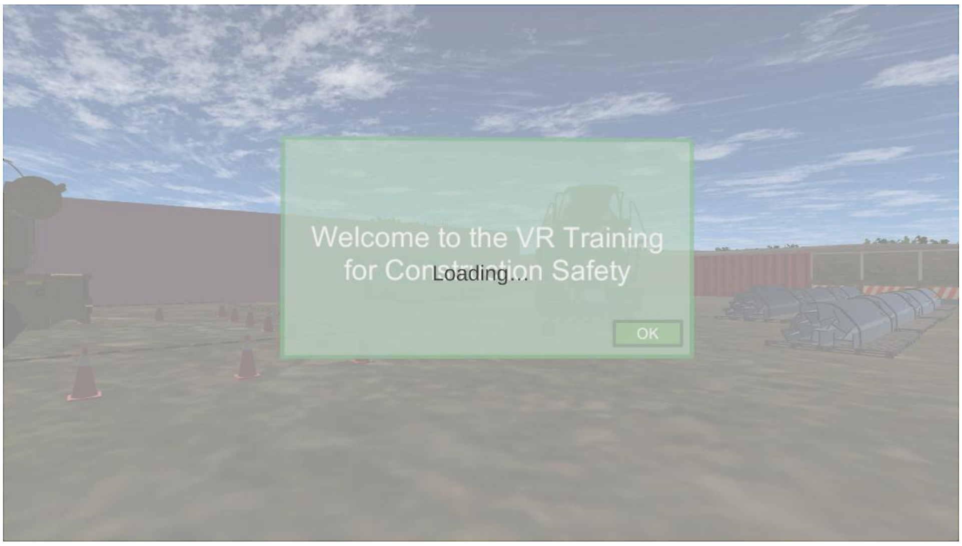


**Figure 25**: Loading Screen before The Main Script Start

- Exit Functionality: Essential exit functionality was implemented to allow the user to close the application with a simple keyboard press. The system is designed to behave appropriately for both development and final use.

- **Build the System (.exe Application)**
  With the development and production phases completed, the final step was to compile the entire VR system into a standalone application. This process transforms the Unity project into an executable file (.exe) that can be launched on any compatible machine without requiring the Unity Editor like we can see in **Figure 26**. This was accomplished using Unity's Build Settings window, where the target platform was configured for Windows (x86_64). All necessary scenes, including the initial loading screen and the three primary training scenarios, were added to the build order.

| | | | |
|---|---|---|---|
| MonoBleedingEdge | 10/16/2025 2:22 PM | File folder | |
| VR Training for Construction Safety_Data | 10/16/2025 2:22 PM | File folder | |
| UnityCrashHandler64.exe | 10/14/2022 5:00 AM | Application | 1,205 KB |
| UnityPlayer.dll | 10/14/2022 5:00 AM | Application extens... | 27,830 KB |
| VR Training for Construction Safety.exe | 10/14/2022 4:53 AM | Application | 639 KB |

**Figure 26**: Standalone Application (.exe)

#### 4.2.2. VR System Flow and Design

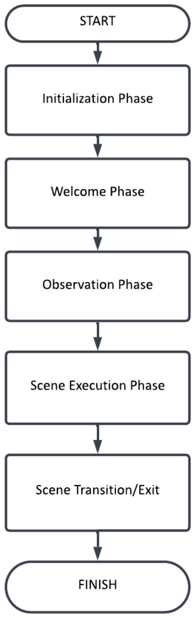


**Figure 27**: VR System Flow Diagram

The overall flow of the VR system is designed to be systematic and intuitive, guiding the user through a structured learning experience from start to finish. The process, as illustrated in the flowchart on **Figure 27** and detailed below, has been refined for clarity and user control.

- Initialization Phase: When the application is launched, it first enters the Initialization Phase. During this technical startup sequence, the system loads all necessary assets, including the 3D terrain, environmental models, and textures, and configures the core XR rig for the user.
- Welcome Phase: Upon initialization, the user is presented with the Welcome Phase. This serves as a brief entry point, displaying a greeting message, a critical reminder to always prioritize safety (e.g., "Remember to Wear Your Safety Gear"), and a prompt asking if they are ready to start the training.
- Observation Phase (Free-Roam Mode): Once the user confirms they are ready, they enter the Observation Phase, which acts as the primary "free-roam" mode of the application. In this mode, the user is placed in the main construction site environment and has complete freedom to walk around and explore all the different areas at their own pace. This open exploration is the central hub of the experience.
- Scene Execution Phase: While in the Observation Phase, the user can approach one of the three designated case scene locations. Upon entering a specific area, they are given the option to start a training module. If they choose to proceed, the application enters the Scene Execution Phase. This phase plays the dedicated animated sequence for that hazard, showing the unsafe condition, the correct prevention method, and the safe outcome.

- Scene Transition/Exit: After a training module is completed, the system enters the Scene Transition/Exit Phase. The user is automatically returned to the Observation Phase (free-roam mode). From here, they can continue exploring, approach and watch the remaining training scenes they have not yet viewed, or choose to exit the application via the designated key command.

### 4.2.3. Rendering and Materials Settings

In this VR construction site, material rendering was applied to create a realistic yet optimized environment suitable for real-time simulation. The overall site is composed of several major material categories that represent typical construction conditions. Given the vast quantity of individual assets and textures employed to create a believable environment, it is impractical to detail every material. Therefore, the description below focuses on the primary material categories:

- The structural buildings are rendered using concrete-based materials with smooth gray tones to simulate reinforced concrete surfaces commonly used in multi-story construction.
- The temporary facilities such as site offices, fences, and storage containers utilize metallic and corrugated sheet textures, reflecting the temporary nature of construction infrastructure.
- The ground terrain employs a blended soil and gravel texture, providing a natural look while maintaining performance efficiency during VR interaction.
- The machinery, such as cranes, mixer trucks, and vehicles, metallic and painted materials are used to simulate reflective industrial surfaces.
- Environmental elements including trees, grass, and hills use lightweight texture maps with baked lighting to ensure smooth performance without overloading GPU rendering.

These general material categories concrete, metal, soil, and vegetation were selected to balance visual realism and rendering performance, ensuring that users can experience an immersive and stable VR environment suitable for safety training applications.

## 4.3. VR Interaction Mechanics

### 4.3.1. Camera and Perspective System

To place the user within the virtual environment as if they were truly there, the camera system is designed to simulate a first-person view (FPV).

- Technical Implementation: This is achieved using Unity's XR Origin, which serves as the user's virtual representation within the scene. The main camera is positioned as a child object of this XR Origin. As a result, any movement or rotation applied to the XR Origin directly affects what the user sees, creating a strong sense of presence.

- Human-Scale Accuracy: To ensure a realistic perspective, the camera's height is set by default to correspond with a normal human height relative to the scale of the virtual environment. This places the user's viewpoint at an average adult eye-level, which is a critical design choice for providing an accurate sense of scale. This allows users to intuitively and realistically judge distances, clearances, and the height of surrounding objects a vital factor in hazard awareness training, especially for scenarios involving falls from height.

#### 4.3.2. Input and Navigation System

The control system is designed to be familiar and intuitive, especially for users accustomed to PC applications and games, which minimizes the learning curve.

- Movement (Locomotion): The user navigates the environment using the standard W (forward), A (left), S (backward), and D (right) keyboard keys. This movement is relative to the camera's viewing direction, meaning pressing 'W' will always move the user in the direction they are currently looking.
- View Rotation (Look Mode): When the cursor is hidden, the view is controlled entirely by mouse movement. This allows the user to look around freely and intuitively, simulating natural head and body rotation. Horizontal mouse movement controls the rotation of the entire character (yaw), while vertical movement controls the tilt of the view (pitch).
- Essential Functions:
  - Cursor Toggle (Q Key): The 'Q' key serves as a crucial toggle between two modes. In the default "Look Mode," the cursor is locked and hidden, allowing the mouse to control the view for immersive exploration. Pressing 'Q' unlocks the cursor, making it visible and free to move on the screen. In this "Cursor Mode," the view rotation is paused, enabling the user to interact with UI elements or menus. Pressing 'Q' again returns to Look Mode.
  - Exit Application (ESC Key): The ESC key is assigned as the command to close the application. This is a standard convention that is easily remembered by most computer users.

#### 4.3.3. Object and UI Interaction

Interaction in this application is centered on deliberate, user-initiated actions rather than automatic triggers, giving the user complete control over when and what they want to learn.

- Scenario Activation via Interactive Markers: Instead of using proximity-based activation, three distinct interactive markers, visually represented as arrows, are permanently placed within the environment at the precise locations of the training scenarios. While in free-roam mode, the user can locate and approach these markers. A simple mouse click on one of these arrows is required to initiate the corresponding training module.

- User-Paced Stage Progression: Once a scenario is activated by clicking its marker, the learning content is not presented as a single, passive video. Instead, the user enters a structured, stage-based progression that they control:
  - Title: User will see what unsafety case they will be learn.
  - The Unsafe Condition Stage: The user first watches an animation demonstrating the hazard and its dangerous consequences. The animation then pauses.
  - The Prevention Stage: A UI prompt appears, asking the user to proceed. Upon clicking, the system plays the next animation, which demonstrates the correct safety procedure or preventative measure. The animation pauses again.
  - The Safe Condition Stage: Finally, after another user prompt, the last animation plays, showing the same task being performed safely, resulting in a positive outcome.

This design effectively links the free-roam exploration phase with the structured learning modules, requiring a clear and conscious action from the user to begin each lesson. After completing the final stage, the user is returned to the free-roam mode, where they can continue to explore or activate another scenario.

# 5. Current Preliminary Results

***The video demo of the using of VR Application Training for Construction Safety are attached in the Moodle Submission and the PPT.***

The project has successfully resulted in a functional prototype of a VR-based safety training application, delivered as a standalone executable file (.exe). The video demo confirms that the core objectives have been met, and the application provides a complete, end-to-end user experience. The key achievements and current outputs are as follows:

- Complete and Stable Application Flow: The application demonstrates a logical and complete user journey:
  1. Initialization: A functional loading screen provides a professional transition while the main environment loads.
  2. Welcome & Orientation: A multi-step UI panel greets the user, provides critical safety reminders, and requires user confirmation to begin, ensuring they are prepared.
  3. Free-Roam Exploration: The user is placed in a fully explorable construction site, allowing for self-directed observation and navigation using intuitive FPV (First-Person View) desktop controls (WASD and mouse).
  4. Interactive Scenario Activation: The three training modules are initiated by the user through deliberate interaction with clear visual markers (arrows) in the environment, rather than automatic triggers.
  5. Structured, Staged Learning: Each of the three scenarios is fully implemented and follows a consistent, user-paced, three-stage progression:
     - ✓ Stage 1: Unsafe Condition: The hazard and its negative consequences are demonstrated.

- ✓ Stage 2: Prevention Method: The correct safety procedure is explained and visually represented.
- ✓ Stage 3: Safe Condition: The task is shown being completed safely, demonstrating a positive outcome.

6. Return to Exploration: Upon completing a scenario, the user is seamlessly returned to the free-roam mode to continue exploring or begin another module.

- Three Fully Realized Training Scenarios: The application successfully simulates the three intended high-risk scenarios:
  - Mobile Crane Overturn Due to Missing Outriggers.
  - Unsecured Materials Falling from an Upper Floor.
  - Worker Falling into a Void Due to Inattention.
- Effective User-Paced Interaction: The use of "OK" and "Play Animation" buttons for each stage is a critical feature. It transforms the experience from a passive video into an active learning process, forcing the user to engage with the information before proceeding. This confirms the successful implementation of the core interaction mechanic.

# 6. Conclusion and Discussion

**Conclusion**: This project successfully demonstrates the viability and effectiveness of using an interactive, desktop-based VR application for construction safety training. The developed prototype achieves its primary goal of creating a risk-free, immersive environment where workers can experience and learn from common high-risk scenarios. The application's design, which combines free-roam exploration with a structured, user-paced, three-stage learning model, proves to be an engaging and effective method for conveying the critical cause-and-effect relationship between safety procedures and accident prevention.

**Discussion**: The strength of this application lies in its experiential learning approach. Unlike traditional training methods that rely on passive information absorption (e.g., reading manuals or watching videos), this simulation allows users to witness the consequences of safety violations firsthand. The visual impact of a crane overturning or materials falling is far more memorable than a textual warning. The risk-free nature of the virtual environment is its greatest asset, permitting the safe demonstration of catastrophic failures that would be impossible to replicate in real-world training.

However, the current implementation has several limitations inherent to its prototype status. The visual fidelity, while functional, is basic and could be enhanced to improve immersion. The primary mode of interaction is indirect (clicking UI buttons) rather than direct physical interaction with virtual objects. Finally, while the application provides the training, its actual effectiveness in improving knowledge retention and changing on-site behavior has not yet been quantitatively measured through user studies.

# 7. Future Implementation and Improvement

Based on the preliminary results and current limitations, the following improvements and future implementations are recommended to elevate the project from a functional prototype to a robust training tool:

- Short-Term Improvements (Enhancements):
  - Enhance Visual and Auditory Fidelity: Upgrade textures to higher resolutions with PBR (Physically Based Rendering) materials for more realistic surfaces. Implement ambient sound effects (machinery hums, wind) and impactful sounds for events (crashes, alarms) to significantly boost immersion.
  - Improve Animation Realism: Refine the animations to be more fluid and physically accurate. Implementing ragdoll physics for falling characters, for example, would create a more visceral and impactful demonstration of a fall.
  - Expand User Interface (UI): Add a main menu for scenario selection and a summary screen after each module that recaps key learning points.
- Long-Term Implementations (New Features):
  - Full VR Hand Interaction: The most significant future step is to move beyond desktop controls and implement full VR controller support (e.g., for Meta Quest or Pico). This would allow users to perform tasks physically:
    - ✓ Instead of watching, the user could grab and place the outrigger pads.
    - ✓ The user could physically pick up and stack materials correctly.
    - ✓ The user would have to attach a virtual safety harness before working at height.
  - Develop an Assessment Module: Implement a scoring and feedback system. The application could track user actions, such as whether they looked in the correct direction to identify a hazard or if they can select the correct PPE for a task. This would transform the tool from a demonstration into a true training and assessment platform.
  - Expand the Scenario Library: Develop additional modules based on other common construction hazards, such as electrocution risks, trench collapses, or "struck-by" incidents involving moving vehicles.
  - Conduct a Formal User Study: To validate the application's effectiveness, a formal study should be conducted. This would involve comparing a group of trainees using the VR application against a control group using traditional methods, then measuring knowledge retention and hazard identification skills to quantitatively prove the benefits of the VR approach.

# 8. References


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