Development of a 3D virtual environment for improving public participation: Case study – The Yuansanze Flood Diversion Works Project

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1. Challenges in current public participation

A large-scale project, such as a flood mitigation project, usually influences sizeable areas of land and may significantly impact rivers, landscapes, and the normal lifestyle of the people living in these areas and surrounds. Ideally, public involvement facilitates the understanding and incorporation of community values into the plans and designs for new infrastructure. Therefore, communication with the various stakeholders, such as inhabitants, landowners and users of the project area, is becoming an important concern for ensuring the success of large-scale projects. Public participation in large-scale projects grew in the United States during the 1960s [1], after which public participation became popular in many countries. Since the late 1980s, as democratization has gradually transformed Taiwan’s political system, Taiwan’s government has encouraged more public participation [2] and thus hearings have become more prominent [3]. In recent years, public hearings have been used by many departments of Taiwan’s government, especially for planning and implementation of large-scale public construction projects. For successful implementation of such projects, the Government must overcome many challenges that may inconvenience stakeholders.

In Taiwan, there are currently three major challenges for public hearings:

1. Lack of engagement: The plan of the project is usually presented using two-dimensional (2D) drawings. This form of presentation makes it very difficult to imagine being in the real environment. There is no way for participants to navigate freely inside the environment and view the scenes from their preferred perspectives.

2. Lack of interactivity: In a public hearing, most of the information is presented through paper-based documents; this does not necessarily require active participation by the audience. Participants may face many difficulties in understanding the plan and finding out the answers they really want due to excess engineering details and lack of integrated presentations. This usually leads to many misunderstandings between the concerned groups, such as presenters, participants, authorities and councils.
(3) **Lack of effective communication:** Plans for large-scale projects usually involve complex engineering analysis, figures and geometric information. These can impede non-specialized participants, who may not be experts in such complex matters, from understanding the contents and objectives thoroughly. Furthermore, most flood control projects involve multi-dimensional information, such as the presentation of water depths in different flood return-periods on a map. Communication may not be fully effective if the presenters can only present the information on 2D media or through CAD charts and statistical diagrams.

These three challenges lead to communication gaps between the decision makers, the engineers, and the public [4].

**2. Communication cycle in public participation**

During public consultation, the communication cycle between engineers, decision makers, and the public will affect the efficiency and effectiveness of the consultation tremendously. A public consultation is usually presented as a hearing that in turn will increase public involvement in decision-making. Issues concerning the public in flood mitigation projects should be addressed in a public hearing, where people can have access to detailed information of the project at hand. Communication gaps between the parties need to be prevented.

Fig. 1-1 shows the conventional communication flow. The designs from engineers were presented to decision makers, usually through some paper-based medium, experiment data, 2D images, and CAD drawings, but this often resulted in a lack of integration with the information. A decision maker needed to observe complex information about hydraulics and geometrics, perform an engineering analysis of the data, and then set the policy. However, it cost time and effort to combine the huge amount of data and sometimes delayed the progress of project. Following these, some public hearings would be held. In a public hearing, decision makers and engineers must explain their policy and engineering details to the public in order to alleviate their concerns about property damage and personal injury when a flood should occur. At the same time, they want to get support for the policy and feedback from the public to revise the design. The public, who are residents in and around the local areas, are mainly concerned about the safety of the design and their lives and properties during floods. Additionally, they are also worried whether the project will influence their daily activities. They want to get assurance from engineers and planners that water will not flow overbank to flood their dwellings during the typhoon season. Unfortunately, the traditional process always consumed much time and was stammered with many misunderstandings, which was also somehow contradictory from a participant’s point of view and sometimes caused disputations. Generally, the public faced difficulties in imagining the project’s impact and the goals that the project ultimately would achieve because most of them had no engineering background in relation to the project, leading to difficulties in understanding construction drawings. If they could not understand the whole project and get assurance from the decision makers, they would refuse to support the policy and on the other hand the engineers found it hard to get constructive opinions during these processes. Additionally, there are many break points in this cycle.

To decrease communication gaps, engineers and decision makers need to explain the design details in a language which is easily understood by the public. One of the major challenges encountered is how to create a better visual presentation for public hearings [5]. Visualization and user interaction has been shown useful for presenting discrete design data [6]. A 3D virtual environment, with advanced technology showing both hydraulic and geometric information, can be an ideal solution [7]. Such an environment is a medium that can be understood by all communities, irrespective of the region or occupations of individuals. Thus, the goal of public involvement through user satisfaction with both the process and the outcomes can be attained [8]. The virtual environment is an effective tool for communication between local residents and the project’s technical personnel. Local residents need more knowledge about engineering and other technical terms and the technical personnel need a better understanding regarding the expectations of local residents. Smooth communication between two parties through knowledge interchange can reduce public distrust and enhance public support in the decision-making process.

Fig. 1-2 illustrates a new communication cycle that employs a virtual environment in the planning and implementation process. Firstly, engineers proceed with their plan and verify their design using experimental and numerical modeling results. They then present their advice and provide consultation to the decision maker with the assistance of a virtual environment display in hope of obtaining greater policy and budgetary support. Concurrent
and subsequent public hearings will be held. Using virtual environments in public hearings, the decision makers are able to give more concrete responses to local queries, and the public can express their opinions more directly and effectively. Therefore, the communication between engineers and the public is greatly enhanced by using a 3D virtual environment to present the project. The exchange and integration of engineering details and flood experiences will be less prone to miscommunications with the use of this superior visual presentation method.

3. Previous work

A computerized virtual environment containing 3D visualization and animation can accurately present a specific imaginary feature to the general public [9], who do not possess a strong knowledge of engineering. Döllner, Konstantin, and Henrik used a 3D virtual environment to display the planning of a public transportation system [10]. They used digital elevation models and aerial photography to build the terrain and laser scanning techniques to build the architecture model. Some navigation tools were built to let the user interact with the virtual environment to see the world from a different viewpoint. Whyte presented a process to transpose CAD data into virtual reality data and pointed out the several related issues such as formats for data exchange, commonalities and differences between CAD and VR, and optimisation of translated VR models [11]. In the process, users can exchange their ideas about the public construction more easily and clearly by using the virtual environment. With effective communication processes in place, public participation was enhanced. Stefan shows the use of virtual reality (VR) models in large construction projects [12], and presented some users’ experiences in using virtual reality models. The results showed that the virtual model was useful for improving the flow of information, and it helped to disseminate technical knowledge to the public.

In the situation of a large-scale hydraulic project, the project display must not only include existing objects, but also objects under construction and still in planning. Most importantly, we need to show how the new structures will mitigate a flood. The 3D virtual environment system does present certain challenges such as how to accurately present the geometric data, the expected result from hydraulic engineering theory, and realistic flood flow phenomena.

4. Case study: the Yuansantze Flood Diversion Works (YFDW) project

Mostly occurring during the typhoon season, flooding is the worst natural hazard in Taiwan, causing serious economic and social impacts [13]. Data analyzed by the Ministry of the Interior, Taiwan, showed that 15,366 people died from typhoon floods during the period 1960–2009, which was about 50% of total deaths due to natural hazards. In order to reduce the flood-related losses, the Yuansantze Flood Diversion Works, one of the largest flood mitigation projects in Taiwan in the last decade, was built over the three years from 2001 to 2004, and it now positively influences around 6.5 million people in the Taipei metropolitan area. It diverted $7.5 \times 10^7$ m$^3$ of water in 18 flood events from 2004 to 2009 [14], and during this period, flooding has not occurred in the Taipei metropolitan area.

The construction site of the flood diversion works at Yuansantze is located at the end of the upper land catchment of the Keelung River. As shown in Fig. 2, the Keelung River Basin has a drainage area of 501 km$^2$ with the mainstream length of 86 km [15]. The Keelung River, one of the three major tributaries of the Tanshui River in northern Taiwan, flows through the Taipei metropolis, the political, economic and cultural center of Taiwan. It is rather steep in the upstream and very flat in the lower downstream; this is ideal terrain for frequent flooding when heavy downpours occur in the basin. Rapid urbanization has resulted in the formation of highly developed and densely populated zones over the Keelung River Basin. However, the hydraulic facilities that existed before the project was initiated were unable to provide secure flood protection. Based on its design, the YFDW project can divert 1310 m$^3$/s of water at the design peak discharge from the upper Keelung River Basin into the East China Sea, while the remaining design flood of 310 m$^3$/s is discharged further downstream of the river weir in the Keelung River [15]. The YFDW project provides an assurance of flood-carrying capacity and significantly increases the safety of the Keelung River Basin under 200-year return-period flood protection.

![Fig. 2. Location of the Keelung River Basin in northern Taiwan.](image-url)
The YFDW consist of four major features: a river weir, a diversion inlet, a 2.48 km-long tunnel and an outlet. The layout of the YFDW is presented in Fig. 3. The layouts of the river weir and the inlet entrance are shown in Figs. 4 and 5, respectively. There is a side weir dividing the main channel of the Keelung River and a sediment settling basin, which traps sediment before being carried into a tunnel. An ogee-shaped diversion weir is designed to generate supercritical flows to prevent the 200-year return-period design discharge from filling up the entrance of the tunnel. In the diversion inlet, a chute contraction as the transition structure with a bottom slope of 10% connects from the ogee-shaped diversion weir to the tunnel entrance (see Fig. 4). During the design period of the YFDW, the measurements of the water levels in the chute contraction were considered the main issue for physical and numerical modelling for the approval of proper design. A physical model of the YFDW was constructed to investigate hydraulic phenomena and water depth while flooding in a different return-period [15]. Based on the dimensions shown in Figs. 4 and 5, the geometric scale ratios of the prototype to the model were determined to be 50 in both vertical and horizontal directions due to the limitations of the construction space. This physical model is an undistorted model with a geometrical scale ratio of 50. The result from a numerical model was used to verify and calibrate the result of the physical model and provide data to the 3D virtual environment.

Many public hearings were held for this project to consult with the public and get their support during the project’s design and construction periods. One of the reasons the Government was able to effectively run the project was the success of the public hearings. In this paper, we use the YFDW project as a case study. It exemplified the use of a virtual environment in public participation. The virtual environment that we designed had already been used in the consultation process to assist Government departments conduct public hearings effectively in this case.

5. Research focus

This paper presents a two-year work development of a 3D virtual environment, with engineering accuracy, for the YFDW project. Our research focus on three points:

First, objects such as buildings, roads, and landmarks in a virtual 3D visualization environment must not only be able to represent the real-world features visually, but also be able to present geometric accuracy at a suitable scale. This enables users to find real locations through spatial coordinates [16,17]. The sizes and shapes of buildings and structures have to be represented accurately so that local residents can sense the severity of a deluge by comparing the water level with the heights of objects with which they are familiar.

Second, the water depth, the velocity, and the process of diverting flood water have to be accurate enough to represent the real situation. This information has to be established based on hydrodynamics from experimental or numerical modeling.

Third, the realistic visualization of complex flow surfaces in the project area is critical. One of the key aspects to enhance the
perception of the virtual world is improving the realism of the flow and wave effects. A more realistic visualization can closely mimic running floods in the YFDW to provide vivid images through consultation with the local community. On the other hand, the cost of production must be considered in order to achieve an optimal outcome.

Some existing techniques could be used to attempt to solve the abovementioned challenges, but we lacked real application and combination of these various techniques. Therefore, we developed a methodology to build a 3D virtual environment with the results from physical and 3D modelling, and data from design and information obtained from the construction site. This is done by combining different visualization techniques such as texturing, rendering, and animating techniques in a virtual environment. The virtual environment with an enhanced web-based interface design allows users nearly unlimited access. Ultimately, we were interested to measure to what degree the implementation of VR influences the overall success of the project.

6. Development workflow

This research contained three stages: physical modeling, 3D numerical modeling, and 3D virtual environment display. The flowchart with inputs and outputs of constructing 3D virtual environments is presented in Fig. 6.

According to the flow, we first needed to collect relevant data. The input data contained a digital elevation model, a layout design of YFDW, hydrological data, and geometrical and topological data. These data sets were used for the physical model and for the 3D flow numerical model. Using input data from the physical model, experiments were conducted for various return-period design floods. In the experiments, photographs and videos were taken to obtain the water-ripple textures and flow patterns in visualization processes, such as running water, waves, reflection and mist. Importantly, from physical experiments we could obtain the information about water depth and velocity field in the physical model.

![Fig. 4. Layout of the river weir, side weir, Ogee-shaped diversion weir, and tunnel entrance.](image)

![Fig. 5. Top view and side view along section A-A of the chute contraction and tunnel entrance of the inlet.](image)
for various return-period floods; this was used as the data source to calibrate and verify the 3D numerical model. Using the 3D flow numerical model, the governing equations were solved, and the flow fields for different return-periods were then simulated.

For the 3D virtual environment, we first used digital elevation data and site survey data to build the terrain and existing buildings. Then we used 2D drawings to build the engineering structures and ensured the accuracy of designing structures in virtual environment. We then collected the aerial stereo photos and photos from the construction site to use as the textures of the terrain and the buildings. The outcomes of the water surface variations and velocity fields from numerical modeling were utilized to construct the 3D model, which was presented along with aerial stereo photographs, geometrical information and topological information. The animations of flood were plugged into the virtual environment, with scene settings being set by the user. Finally, navigation tools were programmed to add the interactive control method. Visualization techniques such as texturing, rendering, and animating were used to create intricate 3D models and animations to display the whole flood diversion works project, including the surrounding environment. Flood scenarios were then shown to generate interactive scenes. With proprietary compression techniques, the size of the 3D virtual environment file was reduced dramatically allowing for viewing over the internet and at different occasions. In a public hearing, the 3D virtual environment could be displayed on a smart board (interactive electronic whiteboard) [18] to increase

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**Fig. 6.** Flowchart of constructing the 3D virtual environment.
the communication efficiency. With realistic scenes and the convenient access, the virtual environment attracted the public to participate and thus the project communication was enhanced.

7. 3D Flow numerical model

We developed a numerical model by means of a finite-volume component-wise total variation diminishing (TVD) scheme. TVD is an important concept for hyperbolic conservation laws [19,20]. The governing equations solved by the finite-volume component-wise TVD scheme as well as the simulated results of the flow fields under the project design flood events at the division works are presented and discussed below.

7.1. Three-dimensional flow governing equations

The governing equations for weakly compressible and variable density (including liquid and gas phases) flows can be written as follows [21]:

Conservation of mass:
\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \]  
(1)

Conservation of momentum:
\[ \frac{\partial \rho \mathbf{V}}{\partial t} + \nabla \cdot (\rho \mathbf{V} \mathbf{V} - \mathbf{T}) = \rho \mathbf{B} \]  
(2)

Weak compressibility constraint:
\[ \frac{1}{\rho} \frac{\partial \rho}{\partial t} + \nabla \cdot \mathbf{V} = 0 \]  
(3)

where \( \rho \) is the fluid density; \( \mathbf{V} = u \hat{i} + v \hat{j} + w \hat{k} \) is the flow velocity in the \( x \)-direction; \( \mathbf{B} = g \hat{k} \) is the gravitational acceleration; \( p \) is the pressure; and \( \mathbf{T} \) is the shear stress tensor; the term \( \mathbf{B} = g \hat{k} \) is the gravitational acceleration; \( p \) is the pressure; and \( \mathbf{T} \) is the shear stress tensor.

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7.2. Numerical methods

The numerical method for solving the governing equations is based on the framework of the finite-volume method. The finite-volume method is a method of representing and evaluating partial differential equations as algebraic equations [20]. Eqs. (1)–(3) are first written in the conservative form as follows:

\[ \frac{\partial \mathbf{U}}{\partial t} + \nabla \cdot \mathbf{F} = \mathbf{B} \]  
(5)

where
\[ \mathbf{U} = [\rho, \rho u, \rho v, \rho w, P], P = p/\rho \]  
(6)

\[ \mathbf{F} = \mathbf{F}_{\text{inv}} - \mathbf{F}_{\text{vis}} \]  
(7)

\[ \mathbf{F}_{\text{inv}} = [\rho \mathbf{V}, \rho \mathbf{V} \mathbf{U} + \beta P \hat{i}, \rho \mathbf{V} \mathbf{V} + \beta P \hat{j}, \rho \mathbf{V} \mathbf{W} + \beta P \hat{k}, \mathbf{V}] \]  
(8)

\[ \mathbf{F}_{\text{vis}} = \begin{bmatrix} 0, \mu \left( \frac{\partial \mathbf{V}}{\partial x} + \nabla u \right), \mu \left( \frac{\partial \mathbf{V}}{\partial y} + \nabla v \right), \mu \left( \frac{\partial \mathbf{V}}{\partial z} + \nabla w \right) \end{bmatrix} \]  
(9)

\[ \mathbf{B} = [0, 0, 0, 0, 0] \]  
(10)

Then, Eq. (5) is integrated over a hexahedral finite-volume cell surrounded by the finite surface. By applying the divergence theorem to this integral, the following semi-discrete equation is obtained:

\[ \frac{d}{dt} (\mathbf{U} \Omega) + \sum_{i=1}^{6} (\mathbf{F} \cdot \mathbf{S})_{i} = \mathbf{B} \]  
(11)

where \( \Omega \) is the volume of the hexahedral cell and \( \mathbf{S} = S_{x} i + S_{y} j + S_{z} k \). In Eq. (11) \( (\mathbf{F} \cdot \mathbf{S})_{i} \) represents the numerical fluxes at the \( i \)-th side of the finite-volume cell boundaries, which includes the inviscid flux, \( \mathbf{F}_{\text{inv}} \cdot \mathbf{S} \) and the viscous flux \( \mathbf{F}_{\text{vis}} \cdot \mathbf{S} \). In the present study, the viscous flux is calculated by means of a second-order central differencing scheme, and the inviscid flux is calculated by the TVD-MUSCL scheme [23]. For time discretization of Eq. (11), the 4-stage Runge–Kutta scheme is employed [24].

7.3. Parallel computation for multi-block grid

In the present study, the simulation domain with complicated geometry can be divided into several sub-domains to obtain the multi-block grids. In the sequential computation, the workload (including computational load and communication load) of sub-domains is only assigned to the single processor, while in the parallel computation the workload of sub-domains is assigned to different processors to compute the corresponding flow fields. Based on the single program, multiple data architecture, the overall computational time can be significantly decreased. Compared with that of the sequential computation, the workload and required memory of each processor are reduced in the parallel computation. However, it should be noted that the efficiency of parallel computation may be decreased due to the uneven workload among processors. In addition, in order to avoid the bottleneck problem due to the communication load between processors, the neighbor–neighbor (N–N) communication approach is used in the present parallel model. The Multiple-Precision Integer library is adopted for the model’s N–N communication instructions so that the model can be easily ported to other parallel machines [25].

8. Simulation and validation for 3D flow field

8.1. Measurements in the physical model for numerical simulations

In the open channel flow, most of the cases satisfying the dynamic condition by the Froude number similarity are sufficient [26]. A physical model should be able to accurately simulate the phenomena which take place in the prototype. Thus, this physical model must have geometric and kinematic conditions similar to the prototypes. As mentioned previously, the physical model of YFDW had an undistorted geometric scale of 50. Based on the Froude number similarity, the flow velocity scale and the time scale are both 7.07, and the flow discharge scale is 17.677. The physical model built in a laboratory is shown in Fig. 7. Experiments in the physical model were then performed to measure the variations of the water depth in several cross-sections.

The experimental results obtained from physical modeling were employed to validate the 3D flow numerical model. According to the experimental results, the flow is confined to the main channel without overflow if the flood discharge is less than the 2-year return-period flood. In the case of the flood exceeding the 2-year return-period, the flow crossing the side weir will be diverted into the East China Sea through the diversion tunnel. The experimental data resulted from 200-year and 100-year return-period design floods which were used in the model calibration and verification respectively, for numerical validation. After validation by compar-
ing with the measured data, the outcomes from numerical modeling were utilized to create the 3D virtual environment.

The simulation domain was divided into 11 sub-domains. The mesh with multi-block grids are shown in Fig. 8. It consists of 27 blocks with 138,375 computational cells. Giving the boundary conditions, the water depth variation is imposed at cross-section A1 (see Fig. 4) as an upstream boundary. Based on the experimental data, the variations of water depth and corresponding flow velocity of \( u(z) \) are given; the other data set is \( v = w = \frac{\partial z}{\partial x} = 0 \). The water depth is given by specifying the corresponding fluid density. The density is set as \( \rho = \rho_w \) in the water region and \( \rho = \rho_a \) in the air region. The downstream boundaries of the simulation domain are located at the cross-section between 0K+150 and the river weir of the main channel. For the downstream boundary conditions at cross-section 0K+150 (see Fig. 4), the velocity gradient was given by \( \frac{\partial u}{\partial x} = \frac{\partial v}{\partial x} = \frac{\partial w}{\partial x} = 0 \), and the pressure distribution was set to be hydrostatic. On the other hand, the measured velocity downstream of the sluice gate at the river weir was specified.

8.2. Simulated results

In the present study, the compressibility parameter \( \beta \) and the turbulent coefficient are calibrated to be \( 10^8 \text{ N/m}^2 \) and 0.1, respectively. Since the liquid and gas flow fields are simulated simultaneously in the two-phase flow computations, the location of the free surface was captured as a discontinuity in the density field. The location of the free surface is determined herein at the position of \( \rho = (\rho_w + \rho_a)/2 \) in the density fields. According to the examination of the depth-averaged flow velocity and water depth at the upstream boundary for the case of the 200-year return-period flood, the resulting Reynolds number is \( 1.26 \times 10^8 \), so the turbulence effect has been taken into account in simulations.

Fig. 9 shows the simulated results of water surface variations under a 200-year return-period design flood. Downstream of the critical section at the oggee-shaped diversion weir, the induced supercritical flow generates oblique hydraulic jumps in the contraction before reaching the section 0K+150. Comparing with experimental observation in Fig. 7, it can be seen that the simulated water surface variations coincide with those in the physical model well at the tunnel entrance. Fig. 10 presents the comparison of the simulated water surface elevations and the experimental data at various sections. In the sediment settling basin, upstream of the oggee-shaped diversion weir between sections 0K+010 and 0K+050, water depth elevations are quite close due to the obstruction of the diversion weir. In the chute contraction between sections 0K+065 and 0K+150, the simulated oblique hydraulic jump is similar to the experimental data at section 0K+125. The experimental data of the 200-year return-period and 100-year design floods used in the numerical model validation provide the outcome.
data of water surface mesh and velocity field, and this is used for visualizing the flood flow and wave in the 3D virtual environment (see Fig. 6).

9. Development of an interactive virtual environment

To develop an interactive virtual environment, we describe the procedures of building the virtual environment of the YFDW, visualizing the flood, and adding human–computer interaction. Among them, visualizing the flood flow phenomena is the most difficult task in this research, which must mimic water surface textures and wave effects to appear more realistic in the 3D virtual environment. It is novel to apply 3D virtual environment technology to the flood mitigation projects in hydraulic engineering.

9.1. Building a virtual environment

There are five steps for the development process of the virtual environment: (1) building the terrain using the digital elevation model (DEM), (2) texturing the terrain using aerial photographs, (3) modeling the flood diversion structure using a CAD model, (4) modeling local buildings and structures through field surveys, and (5) texturing the structures, the nearby buildings and the surroundings, using photographs from the field. The relationship between the elements in the virtual environments and data sources is presented in Table 1 and the following sections will briefly introduce the process of building the virtual environment.

9.1.1. Building the terrain

We use Digital Elevation Models (DEMs) to create the surface of the terrain in the virtual environment. The DEMs data with a resolution of 20 m by 20 m such as that shown in Fig. 11 was provided by 10 River–Management Offices (Taiwan). We analyzed the information of our target terrain in DEMs. The information included the distance, the measurement of area, the topographic cross-section, the gradient, the drainage system, and the watershed. We imported the terrain mesh in DEM into Autodesk 3ds Max [27] and controlled the scale of the model. To ensure operational efficiency, we decreased the face amounts in our model and set 4 vertexes per 100 square meters in the mesh. At the gorge and the lower land, the topography is complex and the change amplitude is high, so we set the eight points per square meters for those locations. Then the surface mesh of the terrain in the virtual environment was created. The DEM includes an abstract representation model of the surface, this helps not only ensure the correctness of the terrain but also provides a solid foundation for the whole simulation.

9.1.2. Texturing the terrain

We used aerial photographs for the terrain textures. The aerial photographs were first converted into image file formats. The images are then edited through Photoshop, an image processing graphic editing software [28]. The brightness, hue, and resolution were adjusted to assure the lucidity of the scene and to include sufficient details. Aerial photographs usually contain geometric distortion due to terrain and camera position. This was removed to make an orthophoto. The raw images were stretched to fit the terrain.

UVW mapping (i.e. texture mapping) was then applied to plot the terrain using our edited aerial photographs. With UVW mapping (i.e. texture mapping) was then applied to plot the terrain using our edited aerial photographs. With UVW mapping (i.e. texture mapping) was then applied to plot the terrain using our edited aerial photographs. With UVW mapping (i.e. texture mapping) was then applied to plot the terrain using our edited aerial photographs. UVW mapping (i.e. texture mapping) was then applied to plot the terrain using our edited aerial photographs. UVW mapping (i.e. texture mapping) was then applied to plot the terrain using our edited aerial photographs. UVW mapping (i.e. texture mapping) was then applied to plot the terrain using our edited aerial photographs.

Table 1

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<th>Purpose in virtual environment</th>
<th>Sources</th>
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<tr>
<td>Building terrain</td>
<td>Digital elevation model (DEM)</td>
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<tr>
<td>Texturing of terrain</td>
<td>Aerial photographs</td>
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<td>Modeling Yuansantze Flood Diversion Works (YFDW)</td>
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<td>Texturing structures, nearby buildings and surroundings</td>
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ping, a 2D map can be converted into 3D. The 3D UVW coordinates are similar to XYZ coordinates, which allows textures editing from aerial photographs to wrap in complex ways on the irregular terrain surfaces in the virtual environments. The points on the texture are assigned to the corresponding points on the surface. This step makes the surrounding environment more realistic.

9.1.3. Modeling flood diversion structure

We introduced the CAD model based on the structure design of the YFDW. The CAD model was imported into Autodesk 3ds Max directly and then built for the 3D model. The detailed information of the shape and size of the structures was already available in the CAD model. To improve on this model we needed to weld lines and unify normal directions, after which we used the functions in Autodesk 3ds Max such as ‘exude’ to transform from 2D to 3D. Then we needed to adjust the scale of the structure according to the terrain model and the CAD model. The 3D models were correctly placed in the virtual environment. The construction of a 3D model from a 2D CAD model can save time and increase the efficiency of the model development. The complex context of flood diversion works projects is an important aspect that engineers and decision makers wish to convey to the public. This was the main use of the accurate data.

9.1.4. Modeling local buildings and structures

We built the approximate 3D model of local hard components such as the houses and temples to enhance the realistic nature of the virtual environment in Autodesk 3ds Max. We went to the construction site and conducted a reconnaissance survey at the Rueigan Village (see Fig. 11), resulting in the acquisition of pictures and general information of shapes and sizes of local buildings. Those pictures served not only to record the size and shape of buildings but also to use for the textures of the buildings in the following step. We also used some preliminary geometrical shapes such as cubes, cones and polyhedrons to build them and adjusted their scale proportionately to the whole scene. For example, the trees were only built as two perpendicular planes. Textures were used to improve the clarity of the visualization of certain details. This step can enhance the residents’ identification of the project details and allow them to feel more immersed in the virtual environment, while at the same time reducing the costs required in surveying and technical drawing.

9.1.5. Texturing the structures, nearby buildings, and surroundings

For 3D virtual environments, visual effects affect the overall quality of the visualization. Photo-realistic texture provides rich information about a real scene [29]. To ensure resemblance between the virtual world and the real-world, textures were col-
lected or created from photographs of interest and from the
description from the CAD model. Some textures, such as roofs
and walls were taken from site survey photographs, whereas oth-
ers like concrete and trees were collected from pictures of similar
materials. Finally some images such as clouds were created di-
rectly in 2D graphic form using Photoshop. The textures were all
edited to various extents, and then applied to the structures in
the 3D virtual environment. Application included material proper-
ties such as color, reflection and opacity. By this stage, the appear-
ance of the model had become realistic. Users, who were familiar
with the local surrounds, could easily find landmark structures in
the 3D virtual environment and could accurately estimate the
height of deluge water at different return-period floods. A detailed
example is presented with the entire engineering structures of
YFDW. The wireframe model of the structure was first created in
Autodesk 3ds Max as illustrated in Fig. 12-1, and then textures of
YFDW structures such as the concrete and gravel were applied in
the model. Fig. 12-2 is the final result after all textures were
applied.

The main engineering structures were realistically presented.
The inclusion of familiar landmarks in the 3D virtual environment
increased users’ engagement with the project and thus enhanced
the communication between stakeholders leading to a better per-
ception with regard to the effect of the project on the local
community.

9.2. Visualizing the flood

9.2.1. Construction of the water surface

The water surface changes due to different return-periods were
imported from the 3D numerical modeling (including water depth
and flow velocity) and constructed in the 3D virtual environment.
From the 3D numerical modeling, we could get the water depth or
water surface elevation at all points of interest. In order to reduce
the face numbers, we decreased the quantity of control points
according to the water surface elevation changing range. As
Fig. 13 shows, water surface variation near the inlet was noticeably
complex, so the mesh density here was relatively high. In contrast,
water surface variation upstream of the oggee-shaped weir was rel-
avatively small, so the mesh density here was set to be low. The
water surface mesh was also separated into several areas according
to different flow directions and flow velocities to present the flood
flow phenomena in the YFDW. Furthermore, some simplifications
and adjustments based on observations of lab measurements were
needed to let the scene seem more natural and realistic.

9.2.2. Rendering of virtual flow and wave effects

In order to improve the realism of the virtual flow and wave ef-
effects, the textures were manipulated. The water effect was im-
proved using alpha blending, texture mapping, and particle
systems. First, we set a water-ripple texture, as in Fig. 13, on the
water surface mesh and allowed it to animate uninterrupted to dis-
play different flow velocities. These water-ripple textures came
from the previously executed physical modeling. An alpha layer like that shown in Fig. 13 was used to increase the brightness of the water surface effect. The reason behind the alpha layer is based on the alpha blending theory; below is a formula of alpha blending used by [30].

\[ C = (1 - \alpha)C_a + \alpha C_b \]  

where \( C \) is the result of operation; there are two images \( a \) and \( b \); \( C_a \) is the color of the pixel in element \( A \); \( C_b \) is the color of the pixel in element \( B \); and \( \alpha \) is the alpha pixels in elements \( B \). Alpha blending is a convex combination of two colors allowing for transparency effects in computer graphics. The value of alpha in the color code ranges from 0.0 to 1.0, where 0.0 represents a fully transparent color, and 1.0 represents a completely opaque color. We could use the alpha layers to build and arrange brighter parts and darker parts of the water surface and to show the waves. In some special cases we could add more than one alpha layer if required by the flow situation. The flow situation of the water surface at the hydraulic jump is more complicated and we added another alpha layer to emboss the movement of water waves, such as in Fig. 13. Combined by adding another three layers, the water surface on the ogee-shaped weir was displayed in the 3D virtual environment, as shown in Fig. 14. The animation of superimposed surface waves made flood flow and waves appear more realistic in the 3D virtual environment.

Additionally, particle systems were used to improve the realism of the water splash effect. The phrase ‘particle system’ refers to a computer graphics technique to simulate certain fuzzy phenomena. Certain emitters were set to act as the source of the particles near the weir and the embankment in accordance with the 200-year return-period flood data (see Fig. 14). A set of particle behavior parameters is attached to the emitters. These parameters include: the spawning rate, the particles’ initial velocity vectors, life time, color and texture. Through adjusting the parameters, the water effects could be shown in the 3D visualization to closely match the lab observations.

The realistic water effects strengthened the confidence that the public had in the simulation and the virtual environment, leading again to more engagement with the project.

9.3. Adding human–computer interaction

The human–computer interaction (HCI) is used to facilitate the interactions between users and the 3D virtual environment. To add HCI, we adopted Virtools, a 3D real-time application software that provides a user-friendly design interface to run virtual reality technology. We used it to develop interactive functions such as the movement of cameras, collision detections, sounds, and controllers in the flood mitigation project virtual world. The controls were found to be very user-friendly and familiar. Everyone was able to control the virtual environment easily while working from home. The HCI design was conducted through iterative prototyping and testing to figure out the best way to build a user-friendly interface.

9.3.1. Navigating in the 3D virtual environment

A virtual camera was created in our 3D virtual environment. We set the relationships between the movement of the camera and the controller, the keyboard and the mouse. By controlling a keyboard or mouse, the users could fly or walk through the 3D environment and zoom-in or zoom-out of a scene easily with the camera-controlling mechanism. They could also see the scenes from several vantage points, with or without the presence of a flood. They could navigate freely around the 3D virtual environment and move to areas of interest. To simulate real-world physics in an acceptable way in real-time, we needed to perform collision detection between the camera and the surrounding environment; otherwise, the users would be able to pass the camera through mountains, buildings, and structures. Moreover, the 3D virtual environment could be displayed and controlled on both laptops and Smart
Boards. When displayed on a Smart Board, the users could be close to the target place by touching and adding mark-ups or comments directly on the screen. This feature helped the progress of the discussion and increased the interactivity.

9.3.2. Situation simulation in the 3D virtual environment

There are five situations of various flood return-periods that we constructed in the 3D virtual environment. We added some 2D entities such as buttons and instructions to indicate the control method. They display at the left of the screen of the 3D visualization environment and formed part of the user-friendly interface. By clicking each of the 2D buttons on the left of the screen, the users are able to view corresponding scenes with water depth and velocity in various flood situations from 2-year to 200-year return-period flood scenarios. The animations of water movements and sounds in each situation differ markedly.

Therefore, a comprehensive understanding of the project can be imparted to a lay person, even though all the technical aspects of the project are shown.

10. Implementation results

10.1. Visualization through the virtual environment

The visualization is displayed through the virtual environment. In the virtual environment, the users can see the flow situation under different return-periods. Fig. 15-1 shows the flow situation under 2-year flood scenario confined in the Keelung River. Fig. 15-2 shows the flow situation under 200-year flood scenario. The users can compare the differences between these two situations including water depths and flow phenomena. In 2-year return-period flood, the water surface mesh is smooth and placid. In 200-year return-period flood, the water surface shows a big drop downstream of the ogee-shaped weir and an increase in flow velocity. Moreover, the environment shows the water splash and mist near the weir. Both 2-year return-period and 200-year return-period flood animations show that the surrounding area is very safe.

In Fig. 16 by choosing to hide the water flow, the main flood control structures stand out at the site and are clearly visible. We
can clearly see the designed details of the weir, the inlet, and the sluiceway, including the designed concrete blocks and gravel materials at the bottom of the stream way. Engineers can use it to explain the engineering details to the public and help the public to understand the engineering details easily. By zooming in the camera and shifting the angle of view point, we can see a park near the levee as shown in Fig. 17. The park is a planned construction in this project, and the residents could come to appreciate that the surrounding environment of the project site will be more pleasant after implementing the construction. These details help the public to imagine the aesthetic surroundings after project completion, which helps the decision maker to get policy support from the public.

10.2. Comparison between the virtual environment and actual views after construction

This 3D virtual environment for the flood mitigation project was built before the construction of YFDW. For the 3D virtual environment to be effective, it must be sufficiently representative of the actual environment after the completion of construction of the flood control project. Comparing Fig. 18-1, an aerial picture after construction, with Fig. 18-2, a picture of the virtual environment with respect to the same viewing angle in Fig. 18-1, we realize that the virtual environment presents an almost complete picture of the site post-construction. Similarity between the simulation and reality is marked for the engineering and technical effects, the landscaping and vegetation, and the buildings in the surrounding areas.

11. Using the visualization for a public hearing

Many public hearings were held for the YFDW project to explain the idea to the public and to gain their support. Before we constructed the 3D virtual environment, the presentation in the public hearings consisted only of verbal reports with the sparse use of 2D diagrams like CAD charts and photographs. The public had concerns over the way the project was presented. Two recurring comments were
Please explain how you ensure that the flood water will not flow overbank along the Keelung River during the typhoons after YFDW completion.

Please give a clear and definite explanation of whether or not the residents of the Rueign Village near the inlet area of the YFDW need to move away.

The 3D virtual environment played an important role in effectively demonstrating the project scenarios to the public and answering questions by helping to disseminate engineering knowledge about all aspects of the project in the public hearings. The 3D visualization technology displays the result of the physical model constructed from laboratory experiments, and 3D flow field models derived from numerical modeling to present an improved communication cycle for the engineers, the decision makers and the public.

The public hearings of the YFDW using 3D virtual environment led to a greater variety of positive responses from the public. There were five main improvements of communication as follows.

1. After presenting the visualizations, 90% of local residents clearly expressed that they would support the works project. By contrast, less than 50% of the residents supported the project before the use of the 3D virtual environment.

2. The efficiency of public hearings has been improved through displaying a 3D virtual environment; the decision makers and the engineers saved a lot of time by not having to explain the complex 2D design-chart. The time used to explain the engineering details was reduced by about 30%.

3. Adding flood simulation in the virtual environment was valuable. The public was very interested in the water effect, leading to a deeper understanding of the engineering background of the project. Many useful suggestions were provided to revise the design such as setting a flood warning system and prettifying the riverside.

4. After the 3D virtual environment went online, the number of visits to the website for the YFDW project soared, to more than 120,000 hits in one particular month; extraordinary for a Government website. During the project, the decision makers and the engineers gathered feedback from the public continuously.

5. The media paid more attention to the project, and pushed the Government to handle the project in a more constructive way.

By viewing the scene after YFDW completion in the virtual environment, the public felt that they would benefit from an improved living area, which would enrich their quality of life. Most
importantly, the participants, through visual demonstrations, could understand the positive impact to be engendered by the new project, even though most of them had no related technical knowledge. They could clearly see all of the structural components within the project territory. They understood the purpose of the project and felt assured about the safety of their lives and properties. Furthermore, of those residents who originally planned to move away, many changed their minds and chose to remain in the local area, Rueigan Village.

12. Major contributions

(1) Using the workflow shown in Fig. 6, we resolved the difficulties of flood visualization in the virtual environment. Based on the engineering accuracy of using the data from experiment and numerical model, the similarity between the 3D virtual environment and the reality remarkably increased the effectiveness of communication.

(2) The project was a real construction. Our system was built based on the project design and our implementation was applied to real public hearings. The approach and virtual environment has experiential success.

(3) The feedback in public hearings shows that using virtual environment can save time and enhance efficiency. The three parties, decision makers, engineers, and the public, all benefited form the interactive communication.

13. Conclusions

In this research, we combined existing visualization techniques and used experimental and numerical modeling results to build a 3D virtual environment for a large-scale flood mitigation project. The environment overcame the challenge of geographical and engineering accuracy and the challenge of replicating flow effects. The implementation was used in real cases of public hearings and yielded positive results.

We investigated the flood flow phenomena in a flood diversion works from the measured data of a physical model. Then we applied a 3D flow numerical model to simulate flow surface variations and velocity fields. These outcomes were used with other reliable input data to build a 3D interactive virtual environment for the YFDW project. The flowchart for constructing the 3D virtual environments was proposed and developed as presented in Fig. 6. Use of the 3D virtual environment to display flood flow and wave visualization established a balance between capability and efficiency, while at the same time enhancing public participation in this large-scale government project. The use of a 3D virtual environment in the public hearings led to a remarkable increase in useful and positive feedback, an increase in public support of the project, and a decrease in the time used to explain the project.

Although this was a preliminary study, we are confident that the techniques will be applied widely in the future to develop new ways of public participation. Also, the techniques have potential for assisting decision makers and engineers of hydraulic projects in planning or implementing processes.

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