Tailings2019 | July 10 - 12, 2019 · Santiago, Chile
tailings@gecamin.com

The benefits of Material Volume Meshes in 3D Slope Stability Analysis: A Tailings Dam Case Study

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ABSTRACT

One of the greatest challenges in performing 3D geotechnical numerical analysis is in creating a model of the geometry of a particular site. A well-defined model that accurately represents the site topography and boundaries of material layers is essential to producing an accurate analysis. For a site with few material units in which the units are cleanly separated and stacked on top of each other, the modelling process is relatively simple. However, sites may have numerous features such as dykes, ore bodies, or other enclosed volumes of material with complex shapes.

The Material Volume Meshes (MVM) is used to handle unusual layered models in situations where the traditional methods present several limitations, as the most common cases like surfaces folding over themselves or negative volume layers. The MVM represents one distinct volume of material composed by a closed mesh shape and any material assigned. Such a material volume could therefore be subsequently represented by a rock or undrained/drained soil constitutive model. The MVM is fully independent and over-rides the layer-cake conceptual model and respects the region boundaries of the model volume during the slope stability analysis.

This paper seeks to demonstrate a case study of a 3D tailings dam numerical model developed using material volume meshes as a starting point for a slope stability analysis. A conceptual model was first developed and then imported directly to a 3D limit equilibrium method (LEM) slope stability software package. The results showed how MVMs can help in obtaining a realistic factor of safety representative of complex geological subsurfaces. The paper also aims to illustrate the advantages of a well-defined conceptual model and what type of field information can be utilized to form a material volume mesh for the purpose of creating a reliable model that adequately represents field conditions.

INTRODUCTION

The use of earth dams to create retention areas for the fine mine tailings is commonplace in the mining industry. The geometry of many tailings dams is complex and typically 3D in nature.

Analysis of slope stability of tailings dams has received increased attention in recent years due to recent tailings dam failures such as Mt. Polley, Canada and Fundao, Brazil. These failures have resulted in increased review assessments of the stability of existing tailings dams worldwide by geotechnical consultants (Fredlund et al., 2017). The most recent failure event of Brumadinho, Brazil in 2019 has accentuated the need of a technical reliability in conceptual and numerical models, due to the necessity of understanding potential failure mechanism for future prevision and risk management.

This paper will examine how 3D Limit equilibrium method (LEM) models are more effective at modeling complex dam geometry but examining the stability at the right abutment of an earthen dam, labelled "Dam 1" fin this paper. Specific focus will be given to how material volume meshes (MVMs) have over come technical limitations to 3D LEM models to accurately replicate geometry that was previously not possible.

MATERIALS AND METHODOLOGY

Why build a 3D Model

Use of 2D LEM models for assessing the stability of real world slopes is based on two assumptions:

- Plane strain conditions are assumed: all slope strain occurs within the plane of the section.
- The geometry of the section is sufficiently similar either side of the cross section, so that out of plane geometry has limited effect on the result.

In the case of many tailings dams the above two assumptions are not met. The lithology of the foundation, geometry of the dam and/or position of the water table can vary across the site resulting in 2D section geometries that can vary significantly with small adjustments in the section's position. These variations can also make it difficult for experienced engineers to anticipate the critical sliding locations and direction (Fredlund et al., 2017) and thus making it difficult to a line the strains occurring in the section with the strains of the true failure.

Therefore a 3D model is needed in order to meet the requirements for proper analysis of a tailings dam at a particular site.

Tailings Dam Model

Like many tailings storage facilities (TSF) the design of "Dam 1" evolved iteratively. After the completion of the starter dam to a height of 62 m, the required capacity for the TSF was increased based on further proven ore reserves. The ultimate height of the dam was then changed from 138 m to 145 m. To accommodate this additional 7 m in height, a number of design modifications where required. Some of the modifications are listed below (the detailed rationale for each modification is beyond the scope of this paper):

- The neat line inclined core slopes would have to be adjusted to provide sufficient core thickness above the original crest elevation.
- A bend of the crest alignment at the right abutment (RA) to allow the dam to key into the natural topography at a higher elevation (Figure 1)
- A transition from an inclined core at the mid-valley to a central core in the abutments (Figure 2)

Dam 1 is a downstream constructed tailings dam. The dam is constructed of a compacted clay core, supported by engineered rockfill. An internal chimney filter prevents internal erosion of the core into the coarse rock fill. Internal erosion of the downstream foundation is prevented with a filter blanket zone. For stability modeling, dam zonation has been simplified based on similarities in material behavior.

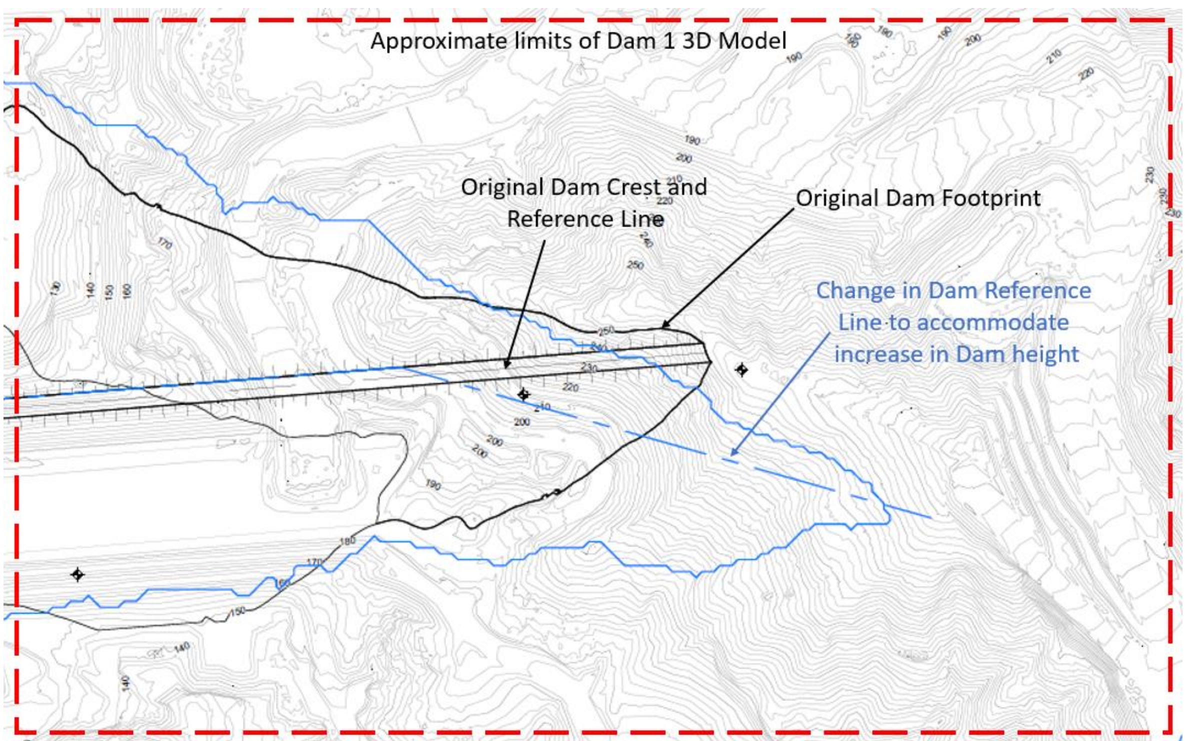

Figure 1. Change in Dam Reference Line and Footprint with Change in Ultimater Dam Height. Original 258 El. Dam in Black, 265 m el. Alignement in Blue.

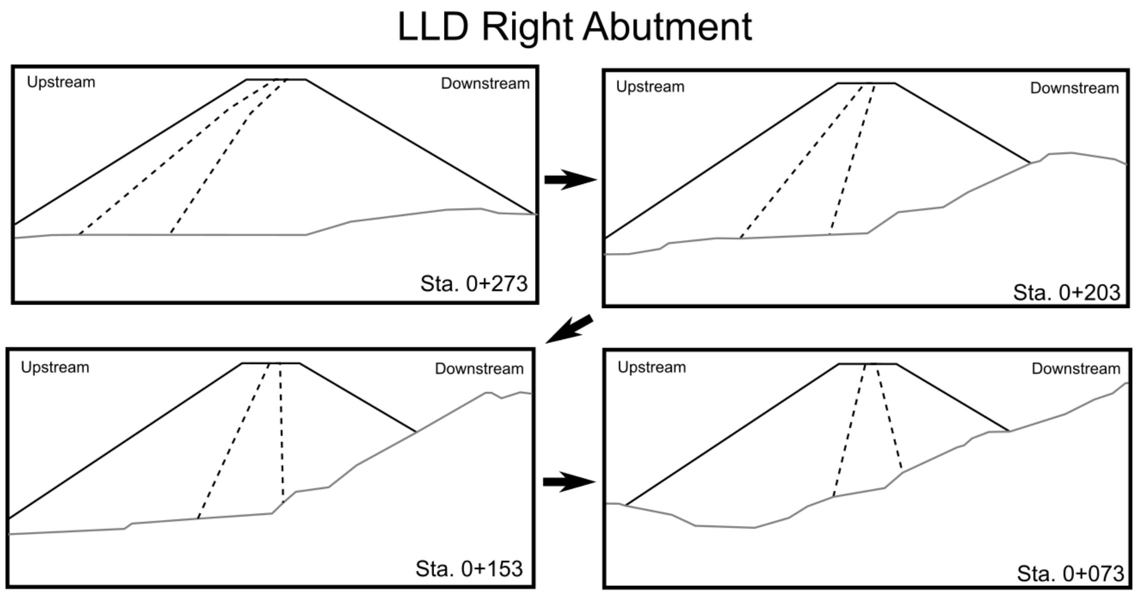

Figure 2. Transition of Core from US inclined Configuration (Top Left) to Central Configuration (Bottom Right). Note at Station 0+153 (Bottom Left), Downstream Face of Core is Vertical Which is Not Possible to Model with a 2.5D Surface

Building a 3D Model

To build the Tailings Dam 3D model, information from a number of sources was used to create the model including: Pre-construction LiDAR, Digitized Foundation approval surfaces, as-build geometry and 2D and 3D CAD designs.

Geological interpretations and borehole data can be included in the modelling process however, for this model a simplified geology was assumed as preliminary stability analysis indicated that upstream (US) stability at the dam bend was controlled by 20 m thick layer of soil immediately under the dam at the location of the bend.

The 3D model was built entirely within SVDESIGNER, a 3D conceptual modeling software package developed by SoilVision (SoilVision, 2018). Pre-development LiDAR was used to define the both the topographic surface and translated 20 m down to bound the bottom of the controlling soil layer in the simplified geology. A DXF surface of the digitized foundation approvals were imported and intersected with both the topographic and subsurface surfaces to replicate excavation of the foundations. The foundation approval surface was also used to create the blanket filter surfaces by translating the surface up the width of the filter and trimming it to the filter extents. As-built dam geometries we imported from Surpac™ and AutoCAD™ with surface mesh refinement editing Performed. Future design stages were either extruded from 2D neat line sections or imported directly from AutoCAD.

To simplify their modelling, many of the surfaces described above where modelled using a special subset of 3D surfaces called 2.5 dimensional (2.5D) surfaces. In 2.5D surfaces are defined in 3D space with each point having an X, Y and, Z coordinates, but with two limitations: 1) the surfaces must be continuous between all adjacent points and 2) the surface can only contain one Z coordinate for each unique X,Y coordinate. This means that unlike a true 3D surface, 2.5D surfaces cannot fold over themselves or allow true vertical faces.

While many of the dam components can be built up with layers of 2.5D surfaces, there are some dam components which could not be modeled as 2.5D surfaces. For these surfaces Material Volume Meshes (MVMs) were needed.

Material Volume Meshes

MVMs are not restricted to 2.5D and exists as enclosed 3D surfaces defining a volume of material. An MVM overrides the materials defined by the layered surfaces of geotechnical conceptual model. This feature is useful for modelling geological layers with extremely complex geometry that usually can't be represented by 2.5D surfaces in a 3D model (SoilVision Systems, 2018).

As described in Figure 2 the compacted clay core transition from an upstream (US) inclined configuration in the central of Dam 1 to a central core configuration at the right abutment (RA). This transition is problematic when using 2.5D surfaces exclusively, for 2 reasons: 1) The downstream face of the core and filters will invert resulting in a location where the surface will be vertical and 2) The order in which 2.5D surfaces would be layered from an inclined core (downstream (DS) rockfill first, then the chimney filters and core followed by US rockfill) is different than the order for a central core (combined DS and US core and chimney filters first followed by US and DS rockfills).

To solve this problem with the geometry an MVM was constructed the available geometry data. The top of the filter blanket was used to the define the base of the Core and chimney filter. The previously designed US and DS surfaces for the core and chimney were imported from AutoCAD and Surpac and used for the sides of the MVM. The top of each stage was created natively within the software. Each individual surface was then tied together like assembling the faces that make up a cube to construct the completed MVM.

Figure 3 illustrates the Tailings dam view with the length of the MVM used.

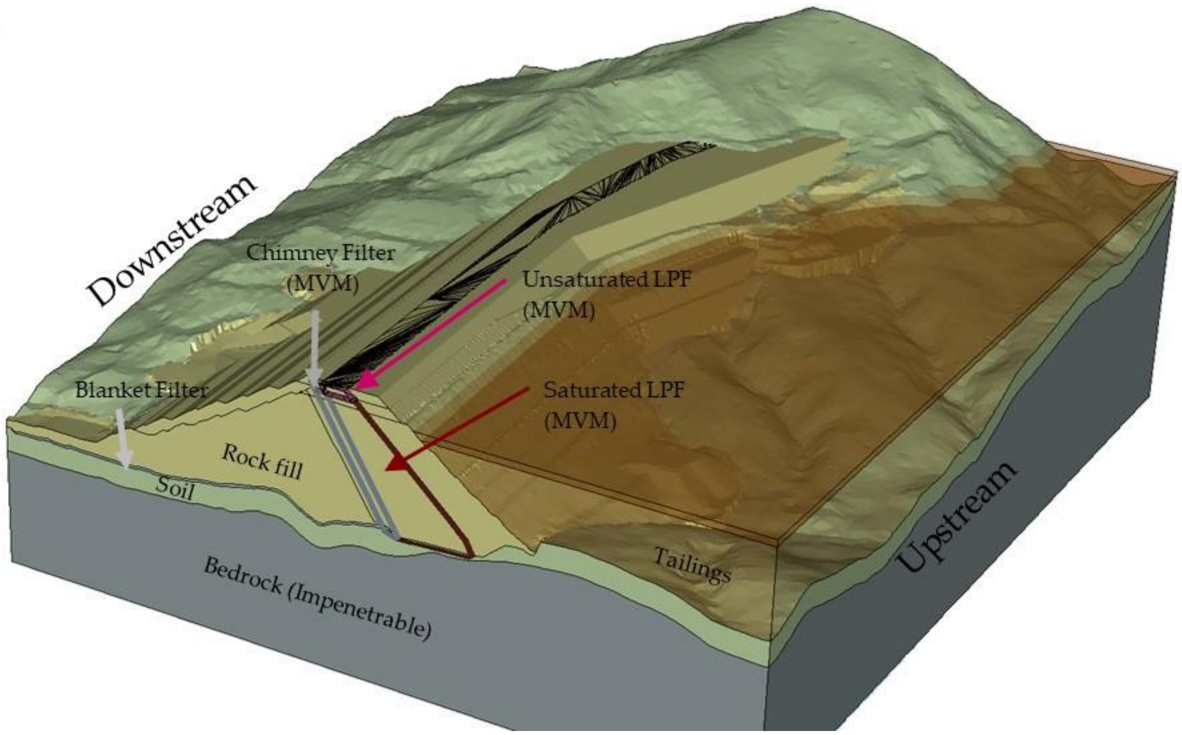

Figure 3. 3D Model of Dam 1, exterior surface for MVM of LPF and Chimney Filter shown

Slope Stability Analysis

The overall stability analysis of Dam 1 includes a number of 2D cross-sections along the dam profile that were analysed to asses the stability of the dam under drained, undrained, and seismic loading cases in both the US and DS direction. The results were compared with established stability criteria. Where this established criterion was exceeded the design was accepted; where the criteria was not met, modifications in the design were made until the criteria was met.

In most cases the conservative 2D analysis exceeded the design criteria and were excepted. However, in the case of US stability at the bend in the RA, 2D sections could not reasonably resolve the pseudo-static seismic stability and a 3D stability model was required. To analyze the LEM slope stability analysis in 3D, the software SVSLOPE (SoilVision, 2018) was used which is integrated with the conceptual modeling software, providing an improved interaction between geometry building and analysis in the final solution.

The 3D analysis illustrated in this paper aimed to verify the US factor of safety under pseudo-static seismic conditions. Based on the site-specific seismic assessment available at the time of the analysis, a seismic yield co-efficient (k_y) of 0.08 or greater was found to meet/exceed the displacement criteria regardless of the height or average shear wave velocity of the slip surface when analyzed using Bray and Travasarou (2017). An orientation analysis was considered to identify the direction of the critical slip surface. Orientations between -40° to 40°from the bisect of the US crest bend angle were considered.

Pore-water pressures (PWP), were modeled within the software using a spatial function. The values of PWP were determined based on which portion of the model was being considered and what PWP primary influence was at that location. e.g. Pond elevation in the US, Filter location in the DS, and construction and pond loading in the core. Exact details of PWPs are beyond the scope of this paper.

The material strength parameters for the foundations and the fills are based on a large number of in-situ and laboratory testing completed as part of a number of site investigation and material characterization programs. Testing includes but is not limited to: Index testing, SPT, direct shear and triaxial tests. Rockfill properties were estimated using the Average Leps shear normal function (Leps, 1970). Tailings were assumed to liquify for seismic analysis. This meant that it had to be modeled using the software fluid model type to allow for the correct material density without being incorporated in the sliding mass.

RESULTS AND DISCUSSION

As shown in Figure 4, the 3D Slope Stability illustrates the slope failure shape for an US analysis using the Morgenstern-Price calculation method and Figure 5 the 2D Slope Stability under the same seismic condition of the 3D model. The 2D cross section for analysis was located at the bend inflexion point.

Results of the 3D stability analysis of the US RA show that the Factor of Safety (FoS) for the pseudo-static analysis with a horizontal co-efficient of 0.08 is greater than 1, indicating that the yield coefficient is greater that 0.08 and would satisfy the deformation criteria at the location in question.

The MVM technique was compared with 2D LEM Analysis that is limited to the plan strain and geometric consistency assumptions, mentioned and discussed above. The comparison between the critical factor of safety of a full 3D model and the 2D section, showed a discrepancy of about 35%, furthermore the 2D model shows a FoS less than 1 for a seismic co-coefficient of 0.08, indicating that the yield co0efficent will be less than 0.08 and the resulting slip surface may not meet the required design criteria. requiring further design to meet the stability criterial resulting in an overly conservative design compared to the 3D analysis.

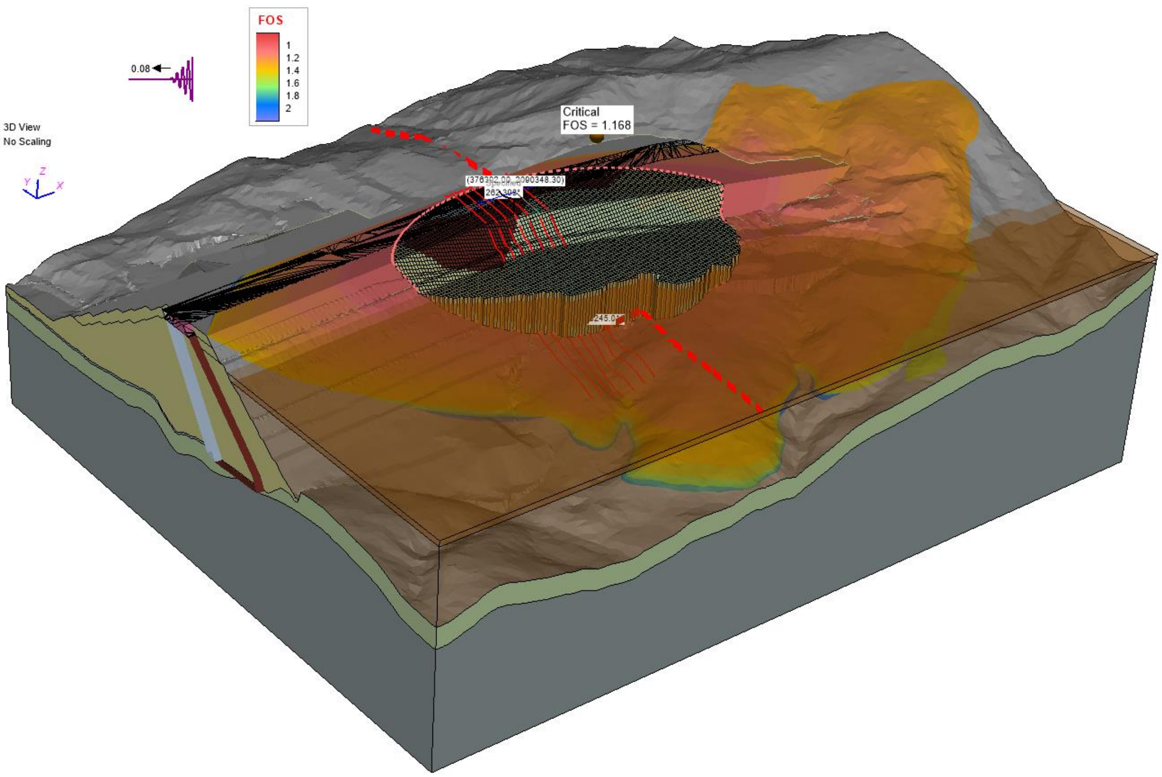

Figure 4. 3D Slope Stability Analysis - US Result Under Pseudo-Static Seismic Condition, Dashed Red line indicates location section cut for 2D analysis.

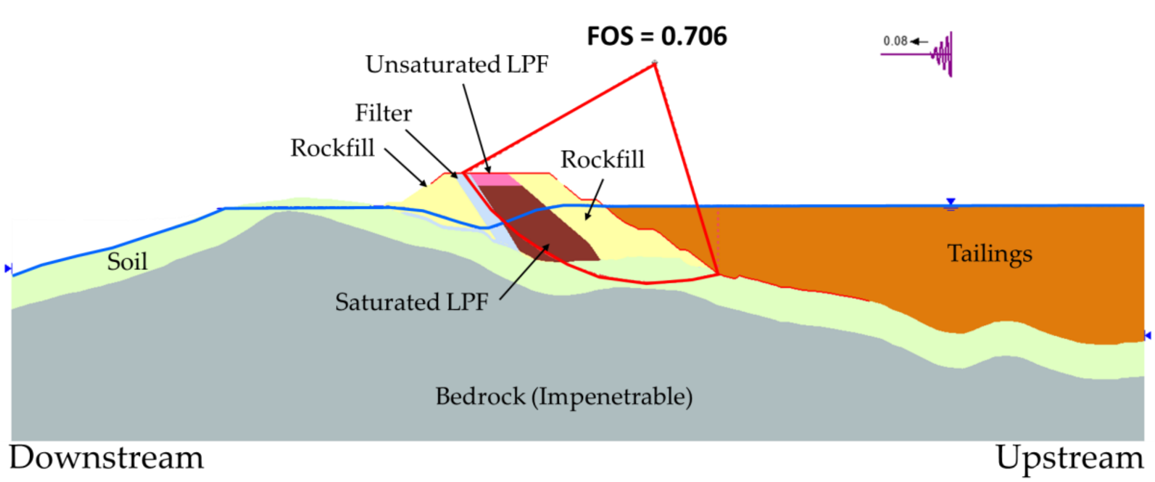

Figure 5. 2D Slope Stability Analysis - US Result Under Pseudo-Static Seismic Condition, Orange is Tailing, Light green is Soil, dark grey is bed Rock (impenetrable). Marron is the compacted clay core, Light grey is chimney and blanket filters. Yellow is rock fill.

Without the MVM the model geometry would not accurately represent the actual design. which could limit the extents over which the model could be applied and also limit the complexity obtained with this 3D model.

CONCLUSION AND RECOMMENDATIONS

Use of 2D stability analysis at the US bend of Dam 1 resulted in an overly conservative stability model. This conservatism can be acceptable if: the design criteria are being met, the resulting configuration is reasonable, and/or there are other factors governing the design at the dam bend. When the stability of the bend its-self is controlling the design, 2D models, which are not able to properly account for the buttressing affects of concave slopes, will result in overbuild and possible impractical designs.

It is important to acknowledge how 3D models in themselves are not immune to poor representations of geometry. Understand the limitations of how the model is constructed is important, just as critical as choosing a modeling package that provides the tools to accurately represent the geometry being analyzed.

Use of MVMs is an effective way to overcome the limitations of 2.5D surfaces while still maintaining the overall simplicity that 2.5D surfaces provide.

ACKNOWLEDGEMENTS

The writers would like to thank BCG Engineering for the case study data provided.

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