STRONGER DAMS, DIKES, AND LEVEES

BEGIN WITH RELIABLE AND ACCURATE ANALYSIS

Take advantage of combined analysis methods with Bentley's Geotechnical Analysis Software

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Earth dams, dikes, and levees are engineered barriers designed to control or retain surface water, either for storing water (for water supply or hydropower) or, even more critically, for flood prevention. Climate change is causing sea levels to rise and is increasing the amount of extreme weather events, making the design of reliable water defenses even more critical.

Tailings dams provide necessary impoundment for mines whose worldwide generation of tailing, which is the materials left over after the process of separating the valuable material from ore, is estimated at a volume of 6 km^3 per year. Recent failures at Fundão tailings dam, Brazil; Mt. Polley mine, Canada; Cadia-Ridgeway mine, Australia; and Córrego do Feijão mine, Brazil, have increased interest in the stability of dynamically constructed earth structures. Our numerical models must align with reality to correctly model the mechanisms which can lead to failure.

COMPLEX **GEOTECHNICAL ANALYSIS**

The analysis of earth dams, dikes, and levees is complex and has multiple levels. An ideal solution integrates a variety of analysis methods and enables a smooth transition when scaling up to a full 3D analysis. These analysis methods include:

- STABILITY ANALYSIS
- SEEPAGE EFFECTS ANALYSIS
- STRESS/DEFORMATION ANALYSIS
- CONSOLIDATION ANALYSIS
- SEISMIC ANALYSIS
- STATIC LIQUEFACTION ANALYSIS
- PROBABILISTIC ANALYSIS

Bentley's PLAXIS geotechnical software helps you perform each of these types of analysis.

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STABILITY ANALYSIS

Bentley offers software solutions for stability analysis using:

- Limit equilibrium method (LEM) with PLAXIS LE
- Finite element shear-strength reduction method (FEM-SSR) with PLAXIS

These solutions are comprehensive and allow for the transition from 2D analysis to 3D analysis. PLAXIS and PLAXIS LE both offer a framework for analyzing a single scenario or a construction sequence and adopting either the total or effective stress method.

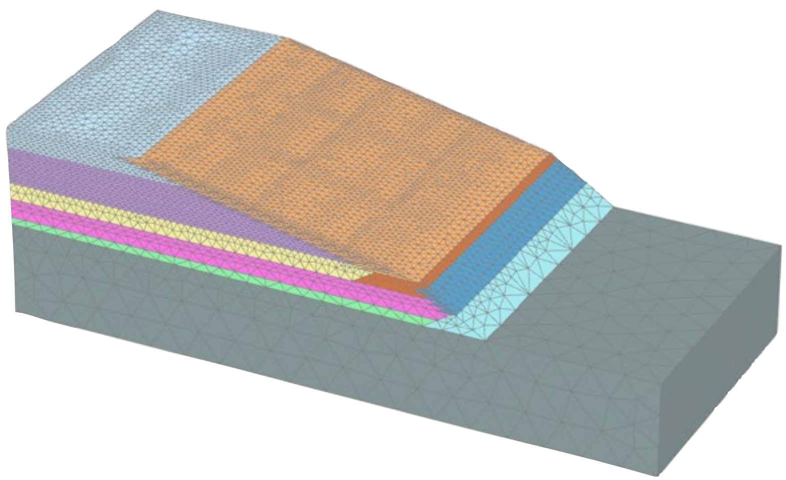


Figure 1: 3D finite element mesh of an upstream tailing dam.

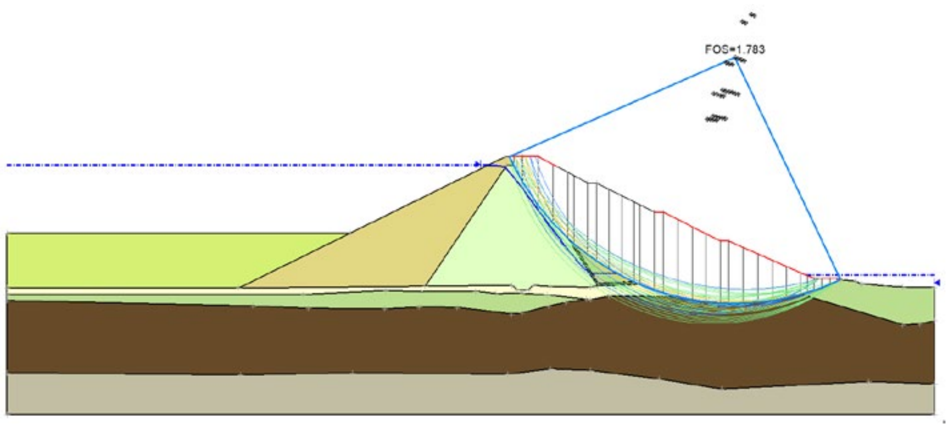


Figure 2: Limit equilibrium calculation of Factor of Safety (FOS) for a typical 2D earth dam.

STABILITY ANALYSIS

Limit equilibrium analysis

The limit equilibrium method (LEM) provides a historically proven and fast method for analyzing the stability of earth dam structures. LEM has been in use since 1915, and the most recent versions of the methods (Morgenstern-Price, GLE, and Spencer) have been implemented in both 2D and 3D. PLAXIS LE offers technically comprehensive capabilities for 2D analysis. With LEM analysis, you gain the following advantages:

- **Distribution of spatial stability in a slope:** Trial slip surfaces give a spatial distribution of many potential failure mechanisms and their relation to the critical slip surface.
- **Spatial stability contours in 3D models:** Determine the Factor of Safety (FOS) distribution in a large 3D spatial area.
- **Significantly reduced analysis time.**
- **Only basic laboratory testing required to support analysis.**
- **Back analysis of specified slip surfaces.**
- **Simple creation of probabilistic analysis.**

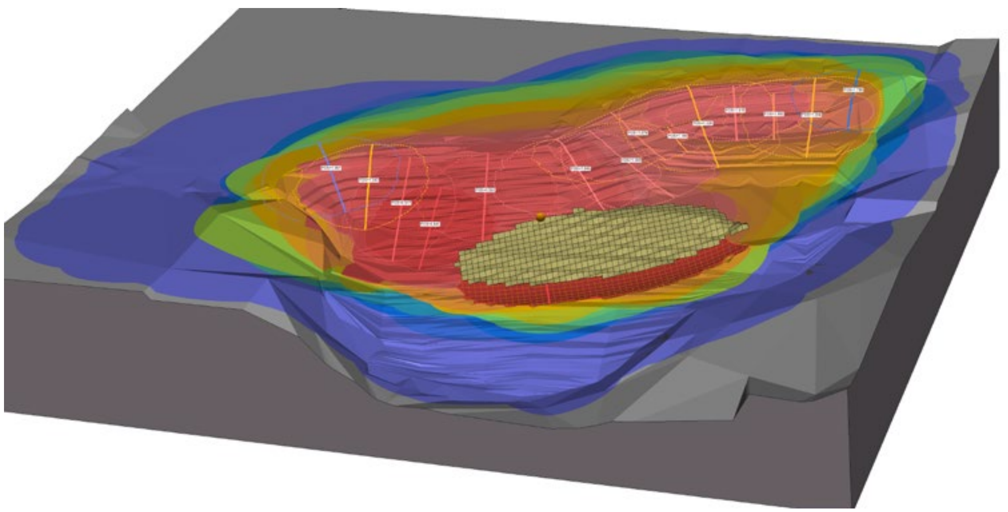


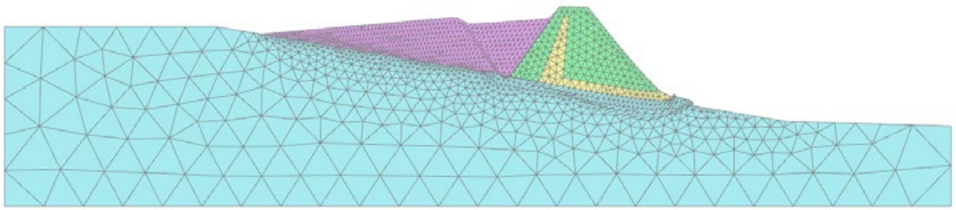
Figure 3: Spatial multi-plane analysis (MPA) of the Fundão tailings dam.

STABILITY ANALYSIS

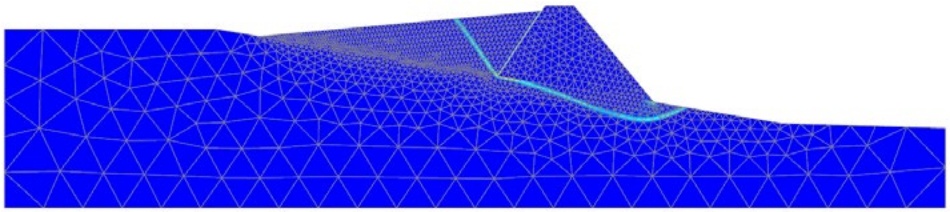
Finite element shear-strength reduction analysis

The finite element method (FEM) is increasingly being applied to slope stability analysis by using the shear-strength reduction (SSR) approach. The concept of SSR is simple: systematically reduce the shear-strength envelope of material by a factor of safety, and compute FEM models of the slope until deformations are unacceptably large or solutions do not converge *(Figure 4)*. The elasto-plastic SSR FE approach provided by Bentley can:

- Eliminate the need for a priori assumptions on failure mechanisms, because the SSR technique automatically establishes the critical failure mechanism.
- End the artificial separation of slope problems into those involving slip surface failures.
- Minimize the expertise required for finding critical failure mechanisms in certain slope problems.



(a) Deformed mesh



(b) Shear strain contour plots

Figure 4: Failure of a tailing dam in PLAXIS 2D.

SEEPAGE EFFECTS ANALYSIS

Advanced designs of dams, dikes, and levees may include internal drains or barriers to trap or collect seepage water, or to dissipate the hydraulic head that drives flow through the dam. The operation of structural water barriers will often involve internally varying seepage pressures, which are of primary importance in stability analysis along with foundation design and construction methodology.

These analyses are useful for predicting the location of the phreatic surface, which is used as an input in the stability analyses, hydraulic gradients for erosion analysis, and seepage quantity and quality for environmental and water management purposes. More specifically, you can control phreatic surface in tailings dams with PLAXIS groundwater analysis features such as:

- Impervious zones, including cores.
- Drainage zones.
- External boundary conditions as a function of time.
- Extensive unsaturated features with access to an extensive database of unsaturated soils.
- Climatic boundary conditions for the calculation of actual evaporation.

PLAXIS finite element analysis software can analyze a variety of technical issues related to seepage control. You can analyze and design seepage and uplift control measures, such as cut-off trenches, slurry walls, grout curtains, and liners.

PLAXIS LE can be combined with PLAXIS Designer for the construction of complex 3D earth structures such as Oroville Dam *(Figure 5)* and the Feijão tailings dam *(Figure 7)*.

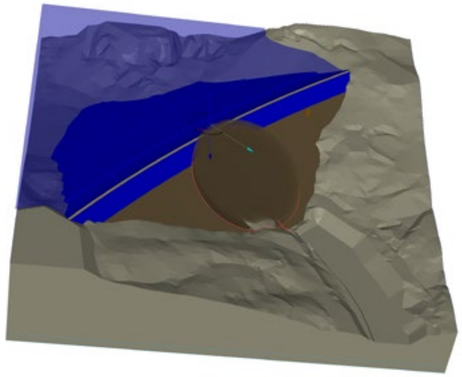


Figure 5: Stability and seepage analysis of Oroville Dam in 3D.

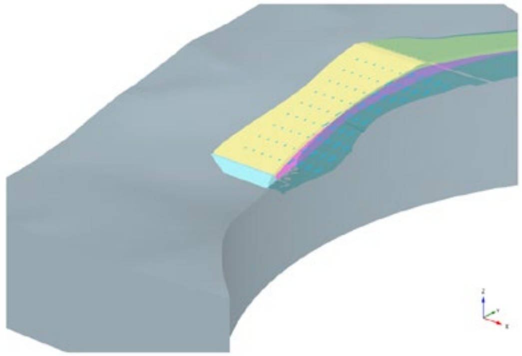


Figure 6: Seepage control of a tailing dam with horizontal drains.

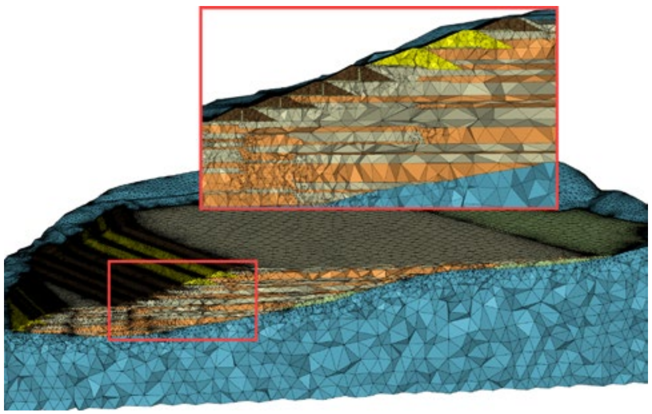


Figure 7: Analysis of seepage at the Feijão tailings dam.

STRESS/DEFORMATION ANALYSIS

The efficient design of flood protection systems such as levees and dikes requires the proper consideration of static analysis, including nonlinear behavior of soil and initial conditions, along with the development of hydrostatic water load and soil structure interaction.

Clay present in foundations can lead to a build-up of pore water pressures if the clays are loaded faster than pore water pressures can dissipate. The settlement of earth dam structures in a valley can lead to cracking issues. Analysis capabilities can determine the extent of these potential issues.

With more than 15 soil constitutive models, a versatile library of structural elements, and extensive water pressure-related modeling features, PLAXIS is the finite element analysis tool of choice for designing reliable flood defenses and guaranteeing optimal safety for flood barriers.

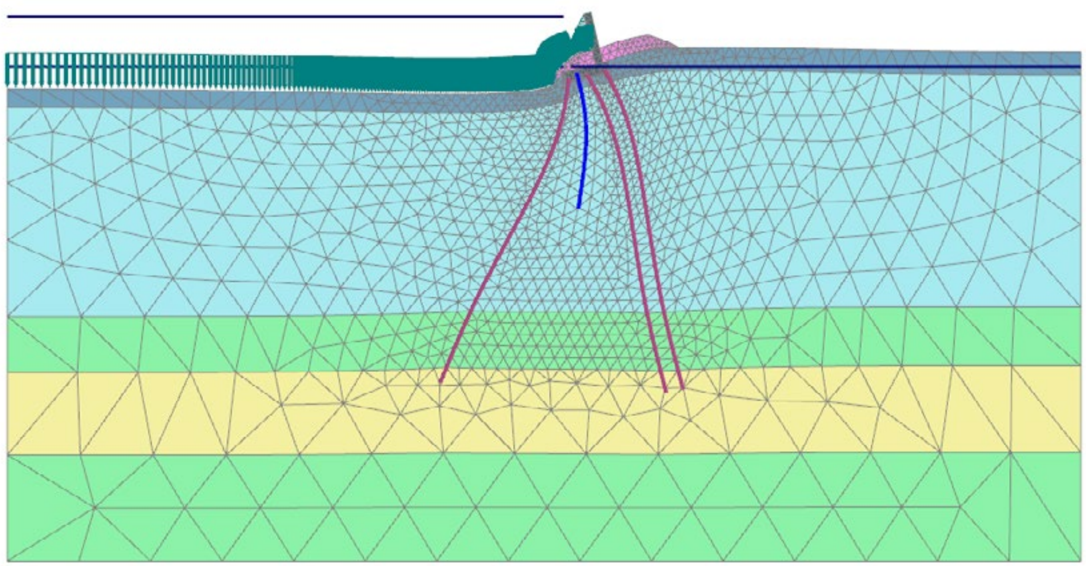


Figure 8: PLAXIS analysis of a pile-founded concrete floodwall system.

CONSOLIDATION ANALYSIS

PLAXIS can also analyze the entire construction sequence of an earth structure, including the development and dissipation of excess pore water pressures during construction by consolidation effects:

- Primary consolidation with the PLAXIS consolidation analysis types.
- Secondary consolidation with the PLAXIS constitutive creep model.

PLAXIS can undertake consolidation analysis in a staggered manner (one-way coupling). Pore water pressure fields are first calculated in an independent, flow-only calculation, followed by a mechanical analysis during which previously calculated pore water pressure values will be read-in and interpreted as body forces. Fully coupled analysis is also possible by simultaneously solving the equations governing the linear momentum balance and the mass conservation for water.

Note that PLAXIS can also account for the effect of consolidation-induced compaction resulting in a significant change of void ratio, and therefore material permeability, to provide more realistic seepage modeling during dam consolidation over a long period of time.

SEISMIC ANALYSIS

Structures must remain stable during operations. Potential natural hazards, such as earthquakes, can lead to liquefaction failure. The geotechnical analysis method must be able to consider responses to both static and dynamic liquefaction failure modes.

PLAXIS can perform dynamic analysis with real earthquake data in both 2D and 3D. The application uses an extensive constitutive model library for modeling soil under cyclic loading conditions with proper and accurate consideration of excess pore water pressure accumulation, which is essential for predicting the onset of liquefaction. Models such as UBC-SAND, PM4SAND, and PM4SILT are available for studying liquefaction in dams.

PLAXIS offers dedicated advanced model boundary conditions for:

- Properly applying incoming shear and compression waves into the FE domain.
- Avoiding spurious wave reflection traveling back toward the model boundaries and meant to be damped out.

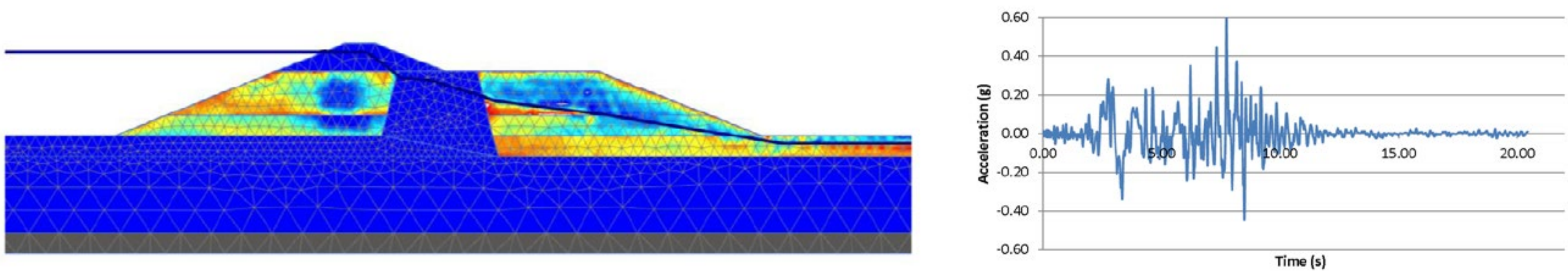


Figure 9: Pore pressure ratio r_u contour plots after shaking on the San Fernando Dam.

STATIC LIQUEFACTION ANALYSIS

Static liquefaction refers to the process whereby a contractive granular material (soils, tailings, gravels, loess, etc.) saturated with water loses its strength in response to an applied static stress. A clear instability such as flow failure appears when permanent loading is higher than the residual shear. This particular case of static slope failure, called static liquefaction, arises due to the rapid increase of pore pressure resulting from an excessive dam rising rate.

PLAXIS offers the well-known constitutive model NorSand which can describe static liquefaction. The NorSand model is easy to use and requires defining relatively few material properties, which are easily measured in conventional laboratory tests. This model can capture the many aspects of soil behavior over a wide range of density and confining stress and can predict the onset of liquefaction from well-graded tills through sands to clayey silts.

PROBABILISTIC ANALYSIS

Increasingly, geotechnical engineers are looking to quantify the performance of geotechnical structures in terms of risk analysis. The analysis software must be able to report results in terms of a probability of failure to integrate with such risk analysis. This is particularly true with levee design.

PLAXIS LE determines the probability of failure using Monte Carlo *(Figure 10)*, Latin Hypercube, or Alternate Point Estimate Methods (APEM). APEM is based on FOSM principles and enables the calculation of the probability of failure with a greatly reduced number of model runtimes compared to Monte Carlo.

Optimal earth dam analysis may also include a representation of spatially varying material parameters. PLAXIS LE can provide them utilizing the Random Fields method. *Figure 11* presents a stability analysis of the Walter Bouldin earth dam considering rapid drawdown by the Duncan 3-stage procedure, as well as the representation of one of the layers utilizing Random Fields.

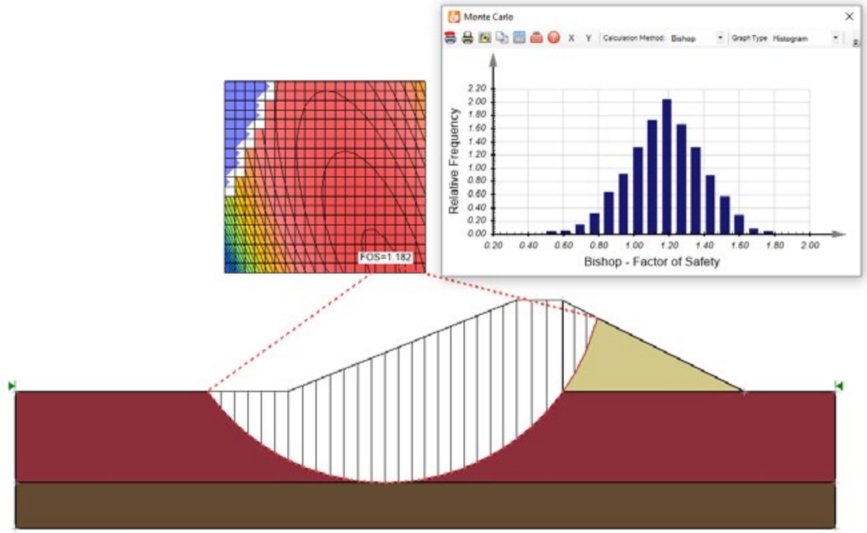


Figure 10: Typical Monte Carlo probabilistic analysis showing the histogram of FOS.

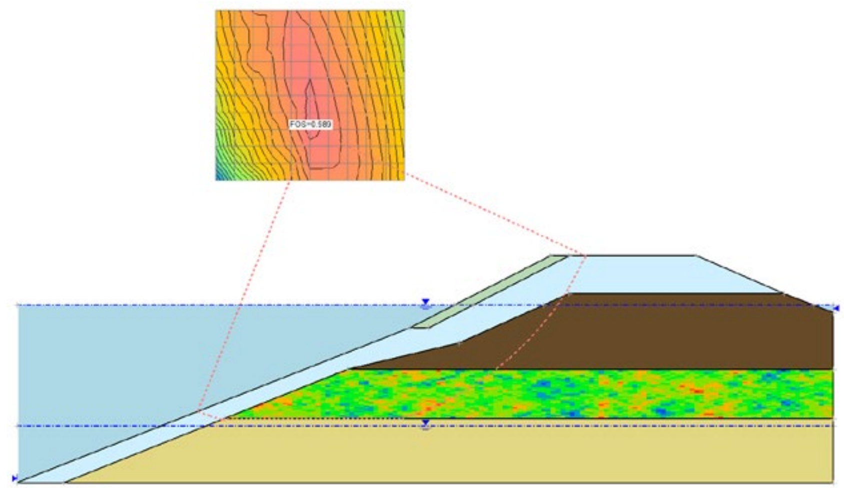


Figure 11: Example of Walter Bouldin Dam stability analysis using Duncan 3-stage rapid drawdown method, considering spatial variability of the friction angle.

REDUCE RISK AND GAIN CONFIDENCE IN YOUR ANALYSIS

Minimize the exposure of risk on your dam, levee, and dike projects. Bentley's Geotechnical Analysis solutions offer comprehensive solutions for both limit equilibrium and finite element shear-strength reduction methods.

Get started with PLAXIS for the analyses of dams, dikes, and levees. You can access powerful analysis tools that will effectively increase reliability in your water defense projects.

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