SEEQUENT

Slope stability analysis with GeoStudio and PLAXIS

How the integrated approach helps engineers work more efficiently, extract better insights, and execute better projects

GeoStudio PLAXIS®

Seequent, The Bentley Subsurface Company

Introduction

In mining, slope stability is both a safety issue and an economic issue. A collapsing slope can put workers in real danger. Plus, catastrophic events like this can bring mining operations to a grinding halt and put a huge dent in profitability.

This kind of incident is a particular worrisome in large open pits, which tend to be significantly less stable and more prone to collapse.

Slope stability has always been an area of concern, but it's become even more pressing in recent years. Mining companies are delving deeper, driving up the risk of destabilisation as they try to maximise the profitability of every site.

Slope stability is equally vital in **civil engineering** since even a small "failure" can have a major impact on the stability of a structure. And, in this industry, stability means safety. Geotechnical engineers must design structures that protect people and the environment, while enduring in perpetuity.

Slope stability is something that can't be overlooked or undervalued. But that doesn't mean it's always an easy process. Engineers rely heavily on numerical modelling to design, evaluate, and assess slope stability problems. But each numerical modelling method has its own quirks and processes, and works best when applied in the right way, on the right application.

Choosing between 2D and 3D analyses can be equally challenging. 2D analyses tend to oversimplify complex subsurface structures and topography, forcing engineers to be overly conservative with their estimations. Or potentially exclude key mechanisms governing stability.

Comparatively, 3D analysis provides a more accurate representation of site geology, offering more geometrical accuracy and accounting for anisotropic conditions more realistically. But 3D analysis also requires significantly more field data — particularly when more complex geological models and more extensive results interpretation are required.

The biggest challenge of any slope stability project is usually, therefore, matching the right forms of analysis to the right use cases.

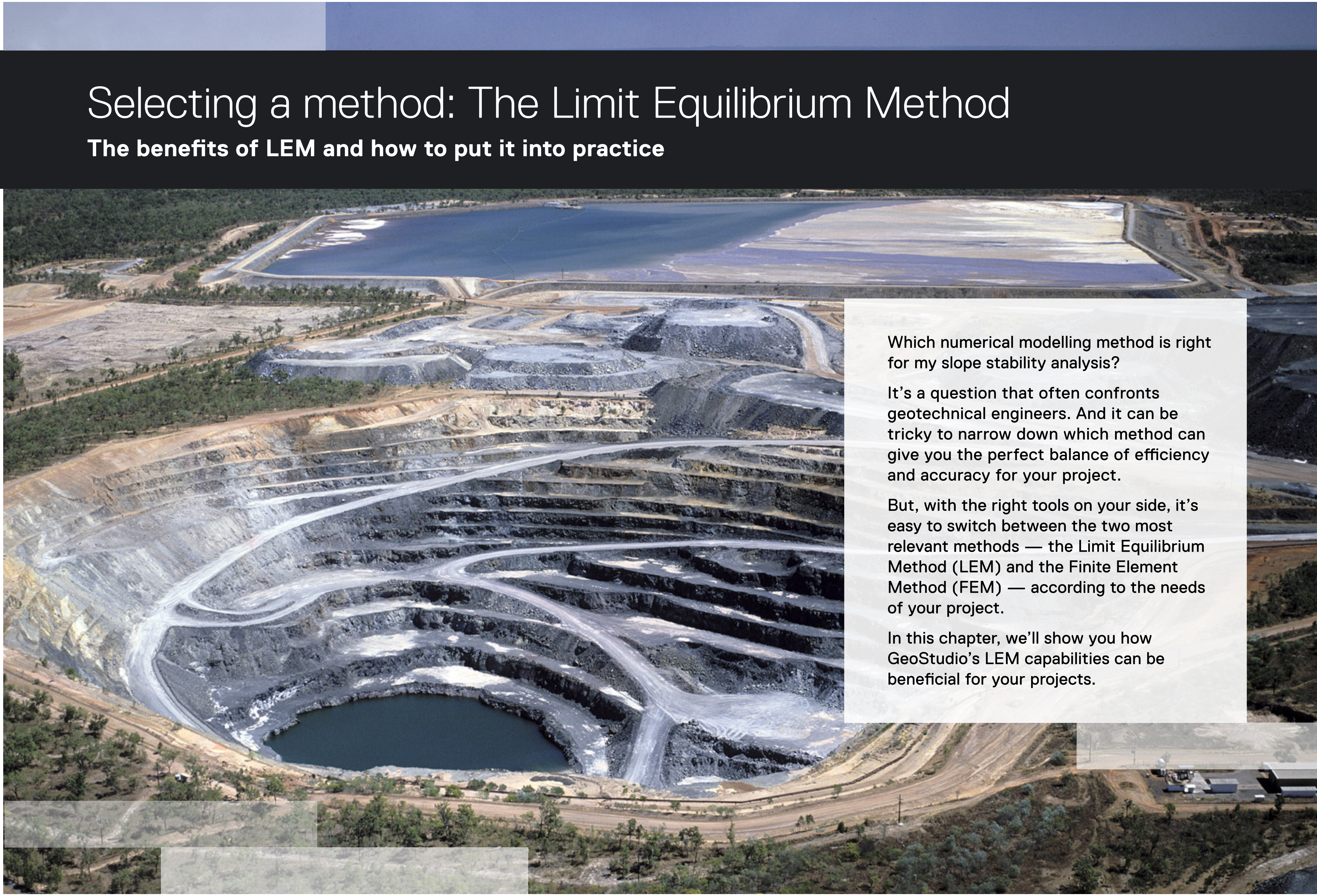
In this eBook, we'll dive deeper into the benefits and drawbacks of each form of analysis. And crucially, we'll show how each of these techniques – 3D and 2D analysis, Finite Element Method (FEM) and Limit Equilibrium Method (LEM) – are complementary. Together, they can give engineers the flexibility, accuracy, and insight they need to keep people safe and projects moving.

Contents

In this eBook, we'll explore:

Selecting a method: The Limit Equilibrium Method

The benefits of LEM and how to put it into practice



Which numerical modelling method is right for my slope stability analysis?

It's a question that often confronts geotechnical engineers. And it can be tricky to narrow down which method can give you the perfect balance of efficiency and accuracy for your project.

But, with the right tools on your side, it's easy to switch between the two most relevant methods — the Limit Equilibrium Method (LEM) and the Finite Element Method (FEM) — according to the needs of your project.

In this chapter, we'll show you how GeoStudio's LEM capabilities can be beneficial for your projects.

How (and when) to use the Limit Equilibrium Method

LEM assesses the equilibrium of a soil or rock mass – in particular its tendency to slide due to gravitational influences.

Through LEM a geotechnical engineer can compare the forces and moments that resist movement with the forces and moments contributing to movement.

The output of LEM is a factor of safety (FoS). An FoS lower than 1.0 indicates instability.

The benefits of LEM

Efficiency
Calculation times are relatively fast with LEM. This means more time to investigate a range of different forms of failure, as well as the different mechanisms that affect stability.

Flexibility
LEM can be applied to a wide range of stability situations, including both natural or anthropogenic slopes. It can also be used for reinforced slopes, allowing you to model a variety of reinforcement types in order to account for resisting pullout and shear forces.

Comprehensive
LEM can represent the strength characteristics of most rock and soil types, from the linear Mohr-Coulomb model through to nonlinear, drained, and undrained strengths. This includes unsaturated and anisotropic options.

LEM can also model pore-water pressure using a number of different methods, including integration with finite element seepage or consolidation analysis. This is crucial; water can significantly impact the stability of a slope, so it's vital to account properly for pore-water pressure.

Easy setup
LEM is relatively easy to set up and interpret. With it, you can quickly evaluate different parts of the slope using a number of different slip surface search methods. This gives you increasing confidence that you understand the critical locations for a potential failure mechanism.

GeoStudio

Running LEM in GeoStudio – the safety evaluation for an open pit

What does LEM look like in GeoStudio? Let's use the example of an open pit that requires a safety evaluation.

1. **Create the 3D geological model or 2D section geometry in GeoStudio**
At this stage, you'll add the geometry and the details of the material properties, including selecting the most representative shear strength material model for each layer. You'll also assign conditions for any weak zones, such as faults, present in the geometry.

2. **Define the LEM analysis parameters**
After selecting the LEM type, you can define the sliding mass using one of several slip surface search methods. Additional components like pore water pressure conditions may also be included in the analysis.

3. **Start analysis**
Once initial setup is complete, the entire open pit domain or a limited sub-domain is analysed in GeoStudio to locate the portion of the domain where failure is most likely to occur.

4. **Evaluate outputs**
In the output module, you can examine the trial slip surface with the sliding masses categorised by their factor of safety. In this way, you can look at the relative risk of different zones of interest. You can then dive deeper into locations of interest to take a closer look at the estimated 3D failure mass and the noncircular critical slip surface in weak zones.

5. **Compare 2D and 3D factors of safety (FoS)**
In GeoStudio, you can assess both the 2D and 3D factors of safety to increase your confidence in the results. In this way, you can reduce your risk by understanding the influence of geometry and material parameter variation on the probability of failure.

Now, let's take a look at what this process looks like in action for an open pit.

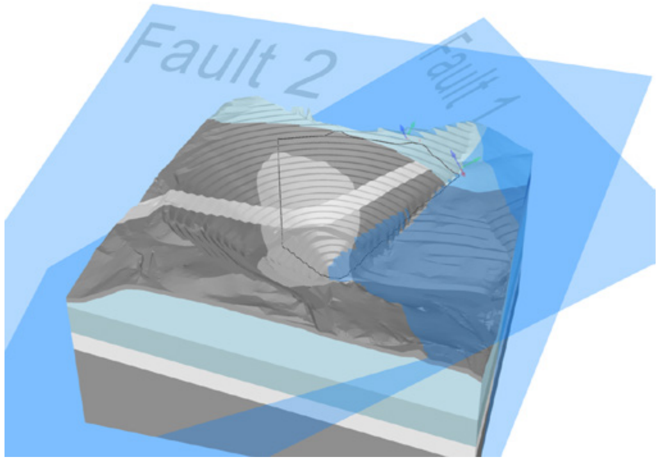
CASE STUDY

Structurally controlled stability of an open pit

The challenge

Structural features like faults and discontinuities control rock mass behaviour, making them important factors in controlling the stability of rock slopes. In many cases, the structure determines the complexity of the failure mechanism, which could range from translational failure to a complex multi-mechanism failure.

In sedimentary rocks, planes of weakness can occur on the bedding, leading to sliding if the bedding daylights. In the same manner, fault planes often generate sliding surfaces or release surfaces. Capturing the impact of these geological structures on the calculated FoS is critical for the safe and optimal design of an open pit.



Open pit geometry including the position of the two major faults.

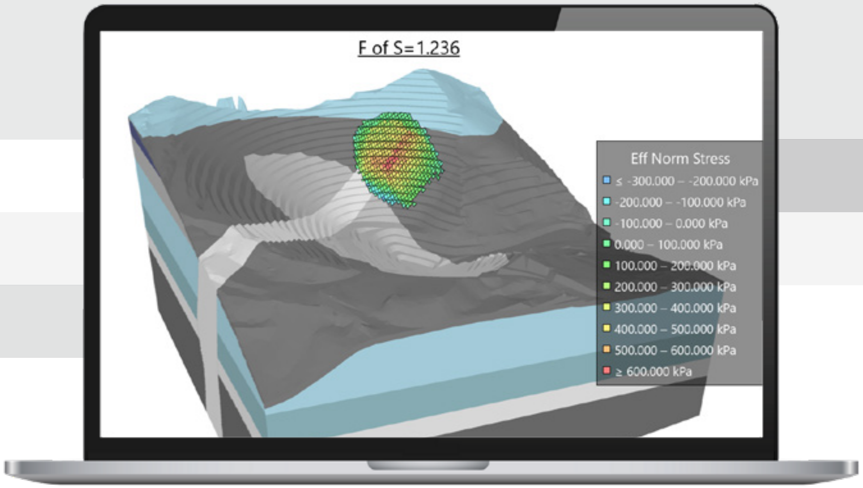
The solution

The first step is to create a geometry that captures the necessary level of complexity in the geology of the site. This was accomplished by building a geological model in Seequent's product Leapfrog, using borehole data and meshed surfaces.

Using Seequent's cloud-based model management solution, Central, the engineer could then dynamically connect GeoStudio with the geological model in Leapfrog and use this to define the 3D geometry.

With the geometry and materials fully defined, the next step was to define the geometry of the faults of interest. In this case, the dip and dip direction of the two structures were measured directly in the field. This data was used in GeoStudio to define the planes, which are then converted into background meshes. The final step involves simply associating a low-strength material model with each fault to represent the strength of a fault gouge material.

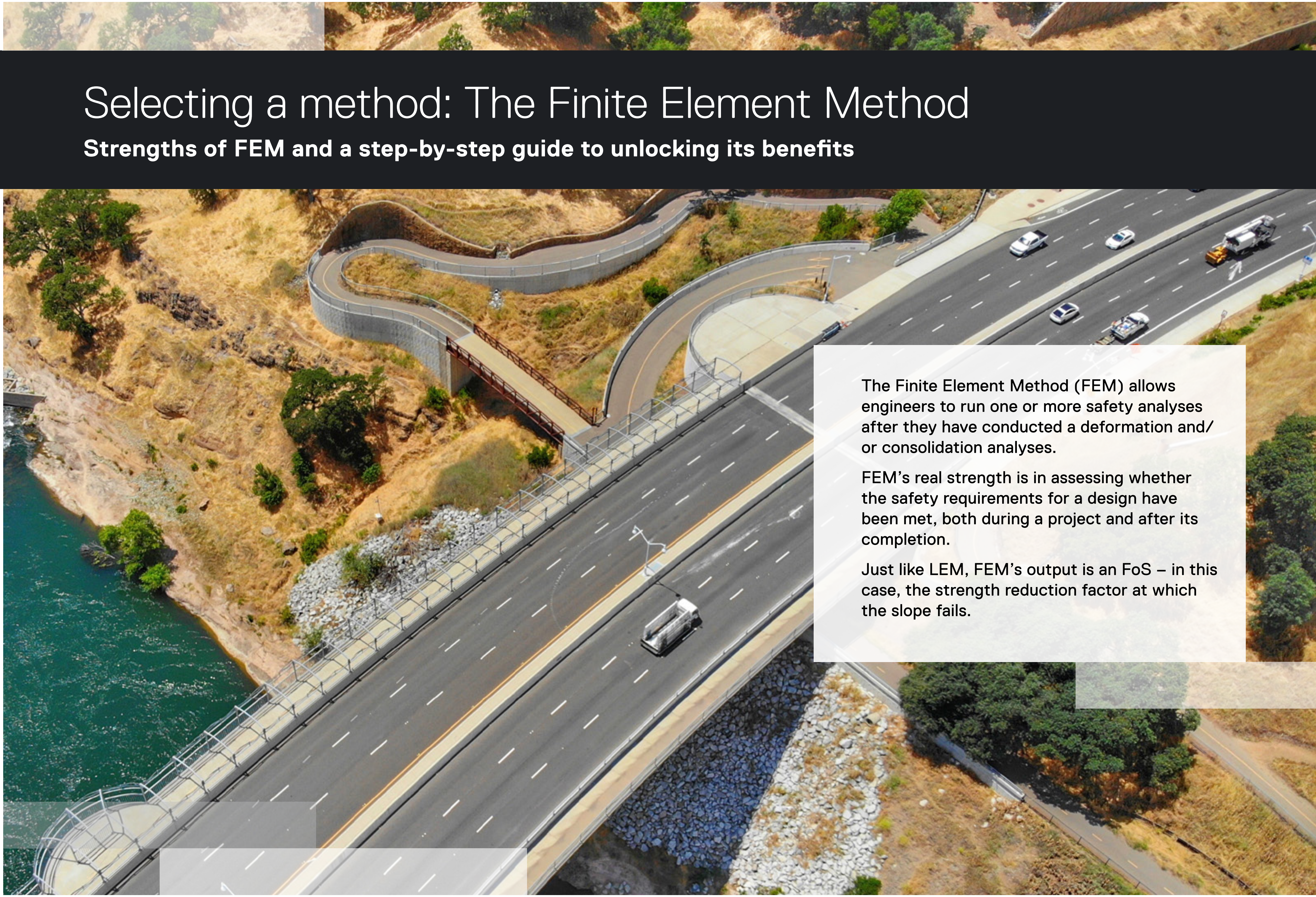
Both the shape and shear resistance of the sliding mass are altered for trial slip surfaces that intersect the faults. The analysis demonstrated that the FoS dropped below an acceptable value when both faults were engaged. More importantly, the quick computation times and easy setup of GeoStudio allowed the engineer to explore the location of the critical slip surface for various scenarios and strength properties.



Critical sliding mass location and associated factor of safety with both faults analysed.

Selecting a method: The Finite Element Method

Strengths of FEM and a step-by-step guide to unlocking its benefits



The Finite Element Method (FEM) allows engineers to run one or more safety analyses after they have conducted a deformation and/or consolidation analyses.

FEM's real strength is in assessing whether the safety requirements for a design have been met, both during a project and after its completion.

Just like LEM, FEM's output is an FoS – in this case, the strength reduction factor at which the slope fails.

The benefits of FEM

Automatic
With FEM, the model will automatically form the most prevalent failure mechanism in areas where the mobilized shear strength is not enough for the shear stress.

Comprehensive
FEM can be used to model both soil and rock, as well as a range of water conditions. This allows engineers to build a more detailed, comprehensive picture of slope stability in a much wider range of scenarios. Which in turn increases the engineer's confidence in the results of their analysis.

Adaptable
FEM gives insight into deformation and allows the slip surface to evolve based on the strength and stiffness characteristics of the soil or rock. It also estimates the resulting stress and pore pressure. Together, these analyses provide engineers with important insight into the safety of the slope, any potential risks, and the stabilisation measures that need to be put into place.

PLAXIS®

Running FEM in PLAXIS

When performing slope stability analysis in PLAXIS, you will need to consider several practical aspects that can incease or decrease the reliabity of the resulting FoS value:

1. Make sure the mesh is refined enough
A mesh that is too coarse will overestimate the FoS. You should also ensure that the safety analysis includes enough calculation steps to enable the failure mechanism to fully develop, as discussed below.

2. Think about the influence of suction
Rerun your prior calculations with suction — it will typically mean that your safety analysis provides higher FoSs. These safety factors will be less conservative, but they'll also be more realistic.

3. Choose where and how to assess your FoS
You can read the FoS directly from PLAXIS' Calculation Information table. But you should generally assess the FoS using a curve plot, selecting a monitoring point in the general area where you would expect to see slope failure. The curve plot is generated after the safety analysis calculation is completed and shows the control point's displacements versus the model's strength reduction factor. In principle, the curve should reach an asymptote that corresponds with the FoS.

4. Check that you have enough calculation steps
A small step or increase in the FoS should lead to a large change in displacement. You can check that this is the case for your analysis by checking your curve plot. If it's not, then you will need to run the safety analysis with a larger number of calculation steps. Inspecting the shade plots of either the incremental displacements (which show the displacements in the last calculation step) or the shear strains will help you identify the failure mechanism that occurs.

A complex tunnelling challenge solved using PLAXIS 3D in highway construction

The challenge

While building a highway from Tepic City to Puerto Vallarta City on the western coast of Mexico, a team of underground construction specialists discovered that a significant mass of rock was sliding close to a tunnel portal. The culprit was an open cut, caused by the reactivation of a geological fault. It was rainy season in the region, which meant that the slope was moving faster than would usually be expected.

The tunnel portal had also started to fail, putting the construction site at high risk.

Combined, these factors indicated that it would not be possible to stabilise the slide and portal failure by conventional methods.

Equally, excavation works to open the tunnel portal were also affected by the unbalanced rock mass. There was a high risk that the work would trigger a huge failure mechanism.

Altogether, the crew were facing a complex geotechnical problem. One that had to be solved fast, for the safety of the onsite teams and the success of the project.

Solution

The team decided to connect the tunnel, the open cut of the portal, and the zone of the landslide with a very rigid cut and cover tunnel, protected by a large concrete pile wall and active anchors.

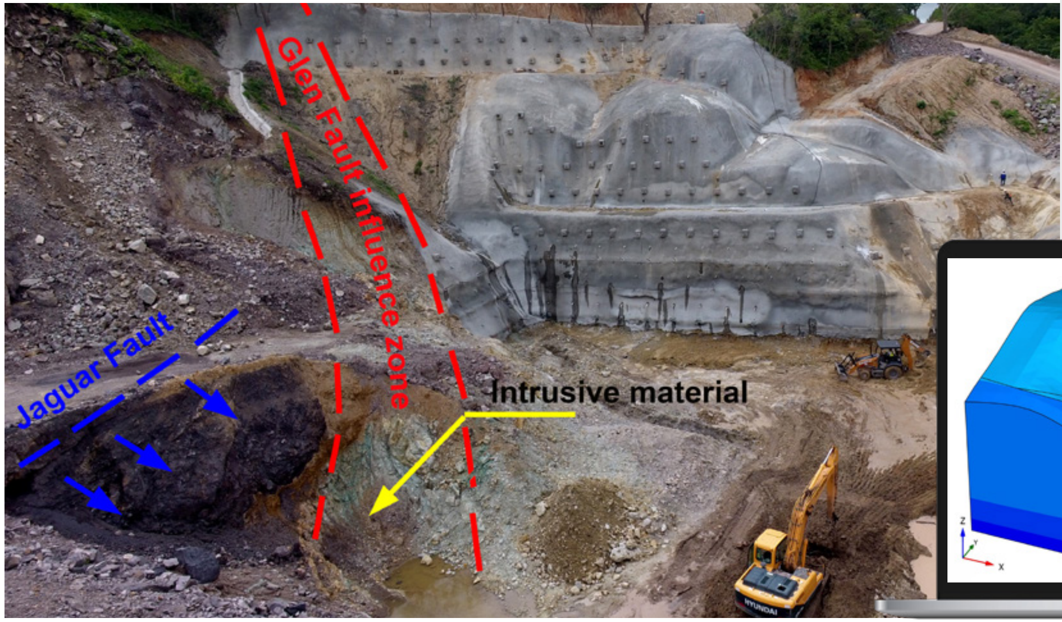
To execute this solution, the team needed to recreate a 3D geotechnical model as close to reality as possible, so that they could accurately model the solution they had in mind.

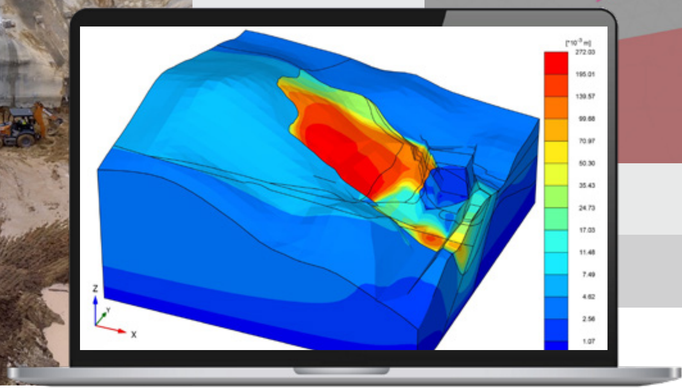
They began with an eight-month exhaustive study of the terrain which included the installation of piezometers, surface monitoring, drilling, and geological/geotechnical mapping of the study area.

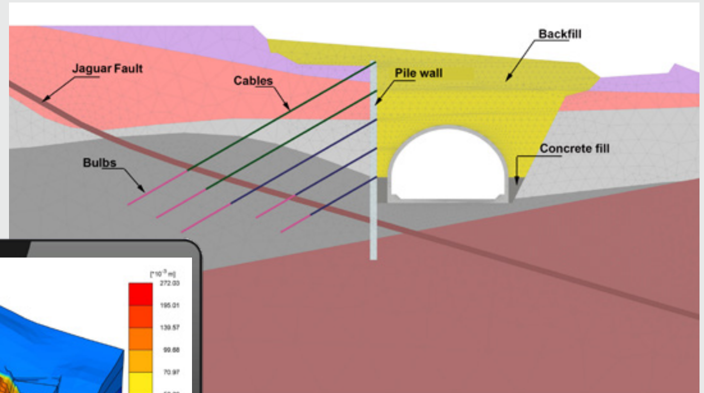
Once the field results investigation was in order, they created a 3D PLAXIS model to represent the movement of the rock mass in the most accurate way possible. They also used a set of 2D PLAXIS cross sections, which were calibrated and used to complement the information of the 3D model with a higher degree of refinement.

Finally, these models were used to calculate the new excavations, structures, and compacted fills of the project.

“Although the proposed solution was not the least expensive,” said Dr Fermín Sanchez Reyes, a lead Geotechnical Engineer on the project. “It is the best long-term and the most cost-effective solution because we were able to calculate and model the safest solution for the stability problem as well as to recover the open-excavation-affected land.”







The best of both worlds: Combining LEM and FEM

How bringing together two forms of numerical modelling deepens your analysis – and saves you headaches

Choosing between LEM and FEM can be a struggle – and many engineers feel as though choosing one method over the other means leaving a gap in their analysis.

But with the right tools, LEM and FEM can complement each other, working side by side to provide a fuller picture of your slope's stability. And increasing your confidence in the accuracy of your analysis in the process.

Running a combined LEM and FEM analysis allows you to consider every factor that could affect the stability of your slope.

Of course, there are some situations where it makes most sense to choose just one of the methods. For example, LEM is perfect for situations where an engineer needs total control over the mechanism under consideration. FEM, on the other hand, provides more insight into deformation and soil-structure interaction for reinforced slopes.

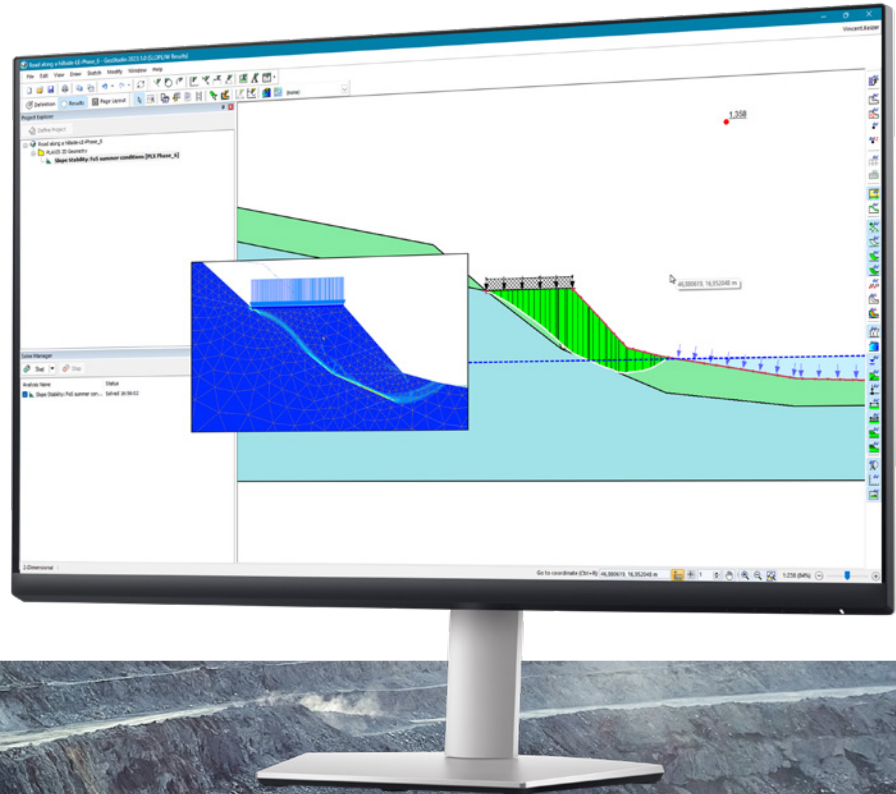
But in situations where more detail is needed, combining the two forms of analysis allows engineers to reach new levels of understanding. Which means you're not forced to make conservative estimates in order to ensure that you have a "failure buffer". Instead, you can deliver your stakeholders all of the accurate information they need to maximise the potential of the site.

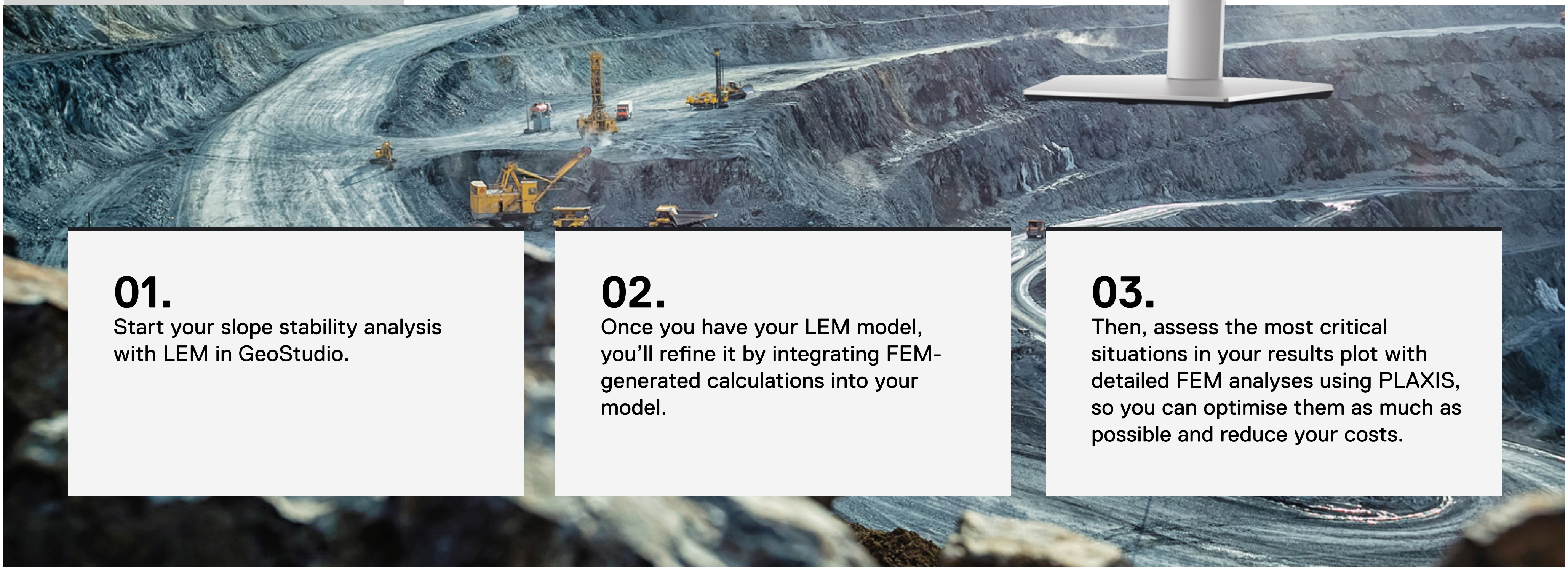
What does slope stability look like with combined LEM and FEM?

For the determination of a Factor of Safety, the strength reduction method is a very powerful tool to obtain the most critical slip surface, a slip surface that may be circular but can also have any other form. However, there may be circumstances in which more information is required than just the most critical slip surface or when the critical slip surface is of minor importance from an engineering point of view.

In these cases, determining a FoS using the Limit Equilibrium Method would be the solution. With Limit Equilibrium, it is possible to specify exactly what part of the model the FoS must be determined while the method would still have the benefit of determining the most critical, possible non-circular, slip surface in that area. It would also allow within one model to determine different factors of safety for different parts of the model.

watch video





01.
Start your slope stability analysis with LEM in GeoStudio.

02.
Once you have your LEM model, you'll refine it by integrating FEM-generated calculations into your model.

03.
Then, assess the most critical situations in your results plot with detailed FEM analyses using PLAXIS, so you can optimise them as much as possible and reduce your costs.

Stability of a road construction project using LEM and FEM

See combined LEM and FEM in action

Let’s take a look at a case where LEM and FEM were used in tandem to deliver a deeper, more comprehensive analysis.

CASE STUDY

Situation overview for the newly constructed road

The challenge

A new road section was being constructed along the shoreline of a tidal bay on the North Island of New Zealand.

Ideally, the road would have been constructed further from the bay in order to reduce the likelihood of instability. But, as the figure above shows, this land was privately owned. As a result, the new road had to be constructed along the steeper gradient next to the shoreline of the tidal bay.

During the first winter after road construction, the road started to tilt towards the tidal bay. There were also concerns about rockfall and landslides above the road.

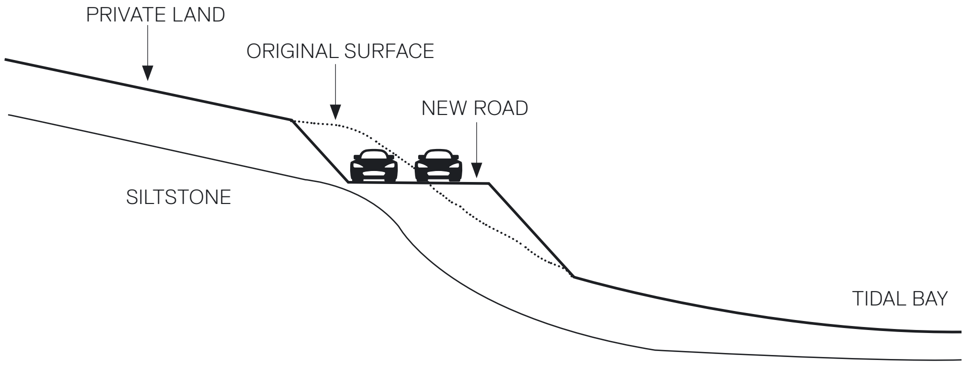
To address these concerns, the team decided to run an additional analysis of slope stability above the road.

However, the complexity of the situation meant that one form of numerical modelling couldn’t provide the detail and accuracy that the team required. The strength reduction method of FEM would give the most critical slip surface, but wouldn’t be so effective at determining a FoS for a specific area. As a result, the team decided to combine FEM with LEM to determine the slope stability above the road.

The main goals of the project were to:

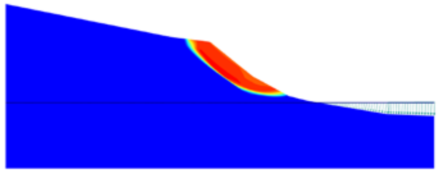
- Determine the FoS of the original hillside
- Model the new road under dry (summer) conditions and calculate its FoS
- Simulate wet (winter) conditions and calculate its FoS
- Apply stabilising soil nails and calculate the FoS in wet conditions
- Calculate the slope stability above the road using LEM

watch video

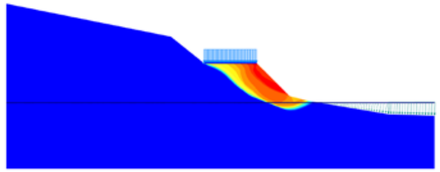


The solution

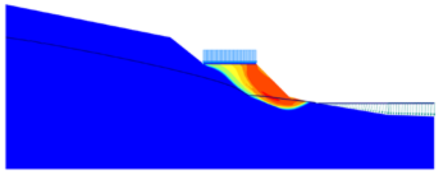
The results of the FEM analysis showed that after all nails have been installed, the most critical area of the slope would vary widely depending on the weather conditions. In winter conditions the slope above the road would require the most attention, whereas in other conditions the slope below the road was found to be the most critical.



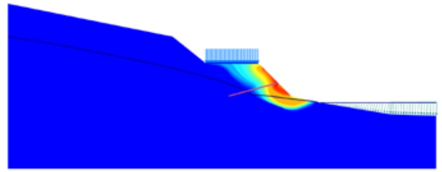
Before construction



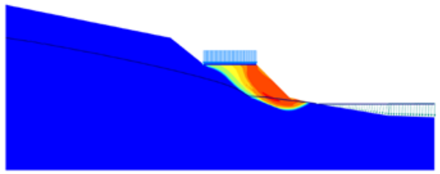
Summer conditions



Winter conditions (no nails)



Winter conditions (top nails)

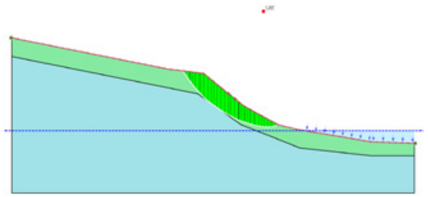


Winter conditions (no nails)

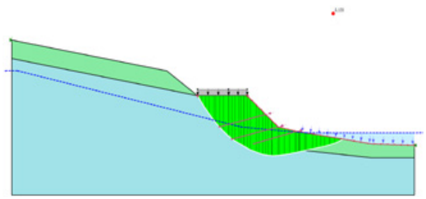
FEM analysis: Incremental displacements showing failure mechanisms

However, the Highway Authority required more detailed information than just the most critical failure. To comply with the Highway Authority's standards, the team would need to determine the FoS against two scenarios:

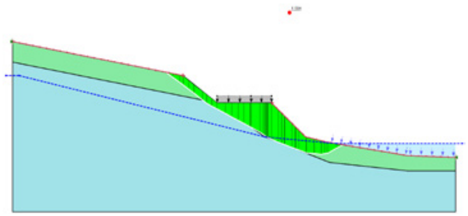
1. **Total loss of the road:**
   reached when either the slope below the road fails or when a failure of the whole hillside occurs. The minimum required FoS against total loss is 1.8.
2. **Temporary loss of service:**
   reached when the slope above the road fails and soil/rocks block the traffic temporarily. This failure is considered less severe, hence the minimum required FoS against loss of service is 1.6.



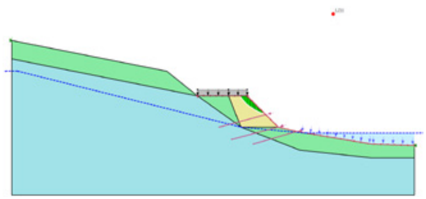
Prior to construction



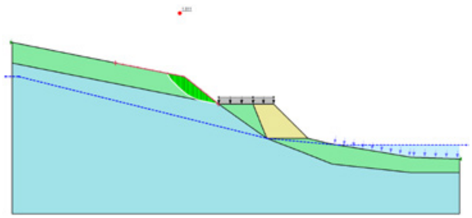
Slip surface below the road assuming strong road



Slip surface for the stability of the entire slope



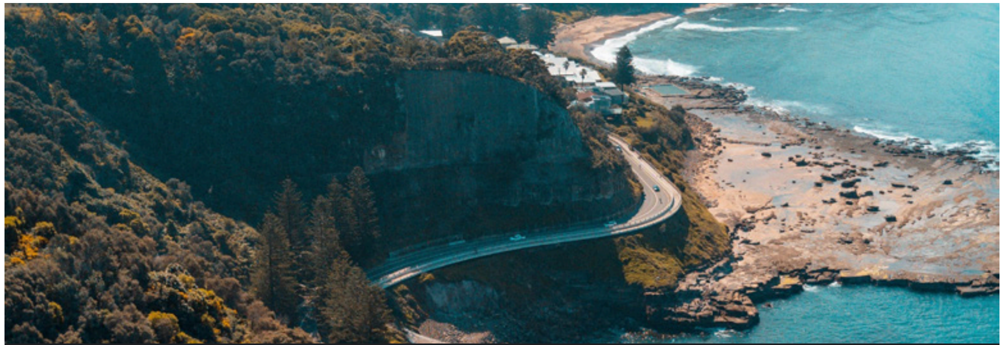
Slip surface below the road assuming weak road



Upper slope slip surface

Still, it was difficult to accurately determine the safety factor of local failure mechanisms on the slope with FEM alone. FEM only provides the most critical mechanism, and couldn't provide safety factors for both the total loss of the road and temporary loss of service.

The team therefore decided to add the LEM method to determine all the relevant safety factors. They ran LEM analysis for the road after construction and with top nails installed in both summer and winter conditions to determine their respective FoSs.



Conclusions

Combining LEM and FEM analysis allowed the team to develop geotechnical designs with significantly more detailed information. This meant that the team had access to significantly more comprehensive results, and also allowed them to extensively verify the conclusions of the FEM analysis by comparing it to the LEM results.

They drew the following conclusions:

- In summer and winter conditions the required FoS against total loss of the road could not be met without additional measures.
- In summer and in winter conditions the required FoS against temporary loss of service would be met, hence no additional stabilising measures are needed for the slope above the road.

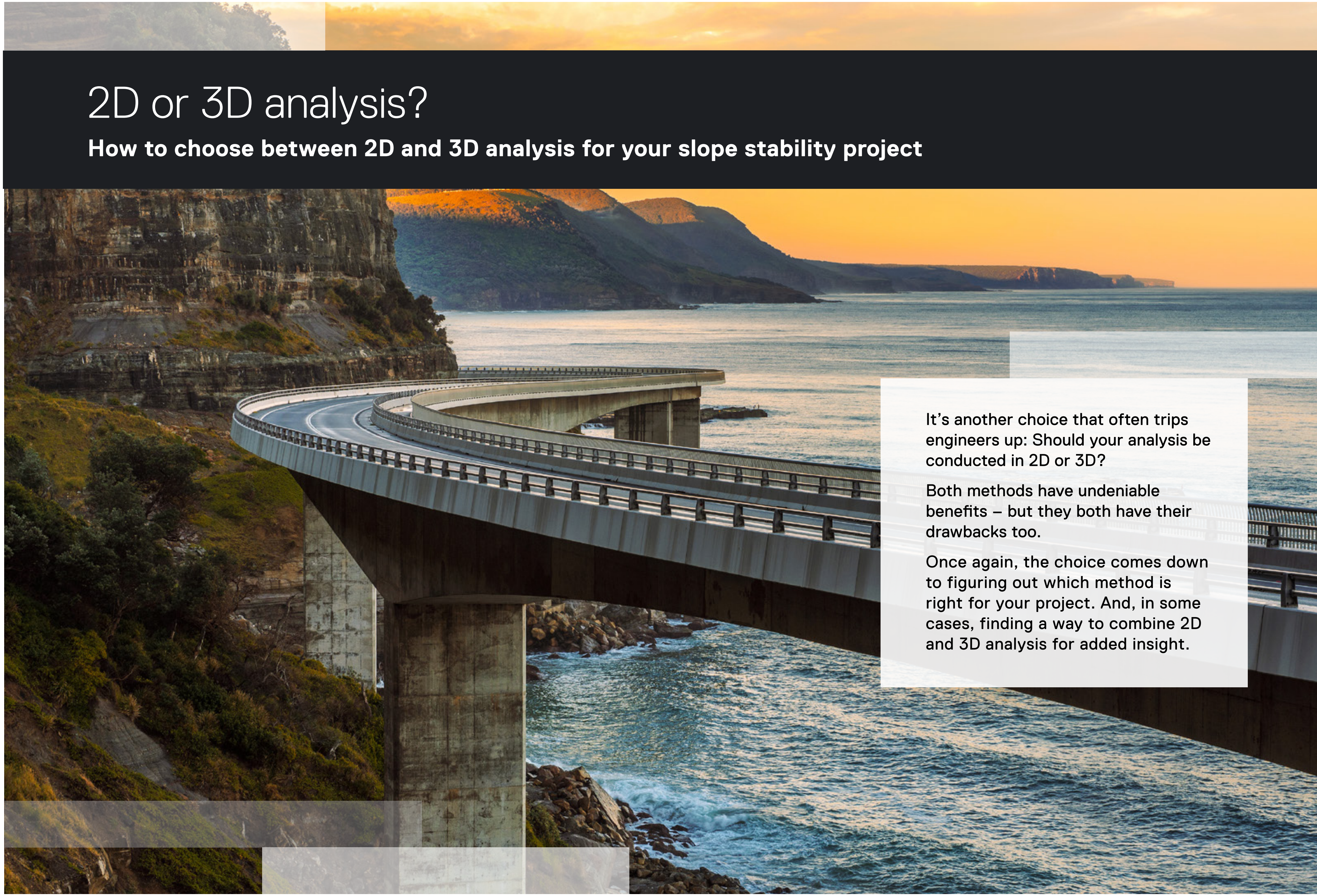
When installing one row of soil nails, the required FoS may be reached according to the LEM analysis but it depends on the (uncertain) reinforcing influence of the road.

- When all soil nails are installed the required factor of safety against both total loss as well as loss of service are met though some concern may remain for local failure just under the edge of the road.
- Installing all soil nails is probably the best way to ensure the stability of the road.

The team found that combining FEM and LEM allowed them to easily address varying requirements for safety factors without sacrificing efficiency or accuracy. In this case, using FEM allowed them to find the most critical slip surface at any project stage, while LEM analysis allowed the team to uncover FoSs against other critical eventualities – like total loss of the road and temporary loss of service. Crucially, the LEM analysis could be validated against the results of the FEM analysis; both methods were integral to the project's success.

2D or 3D analysis?

How to choose between 2D and 3D analysis for your slope stability project



It's another choice that often trips engineers up: Should your analysis be conducted in 2D or 3D?

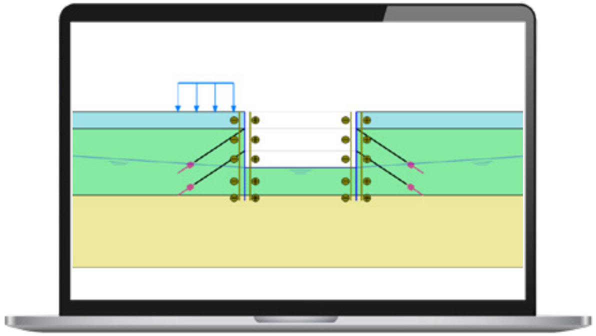
Both methods have undeniable benefits – but they both have their drawbacks too.

Once again, the choice comes down to figuring out which method is right for your project. And, in some cases, finding a way to combine 2D and 3D analysis for added insight.

Keep it simple with 2D...

2D analysis might be the less detailed option, but it has a couple of benefits that mean it's still suitable for many projects: faster setup and faster solve times.

2D analysis is typically easier to set up than 3D analysis, meaning it takes significantly less time to complete tasks like defining the geometry. And, since the resulting model is much smaller, 2D analysis tends to have much faster solve times than its 3D counterpart.



When should you use it?

2D analysis is perfect for applications that don't have 3D mechanisms controlling stability. Use it for projects with near linear and uniform geometries, relatively simple pore-water pressure conditions, and isotropic material properties.

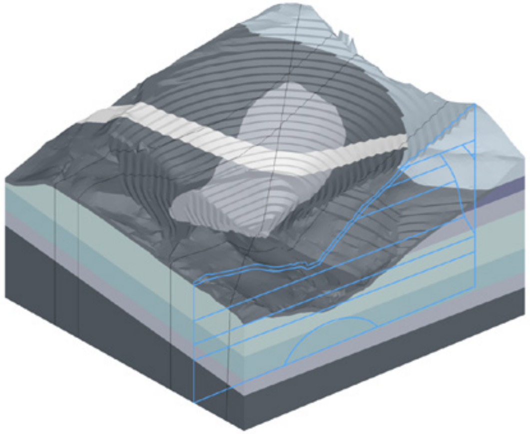
When should you use it?

In applications that involve complexities in geology, groundwater, geological structure, and topography. Anything where lots of different factors affect the stability of your slope — and where you require a high degree of certainty to move forward.

If you've already run a 2D analysis and are wondering whether you might need a 3D model, ask yourself these questions:

- Can the nature of the real 3D geometry have a negative impact on the 2D FoS value?
- Or a positive effect to reduce design and construction costs?

If the answer to either question is yes, then it's probably time to think about creating a 3D model.



...or dial up the detail with 3D?

3D analysis is significantly more geometrical detailed than 2D.

The major drawback is that this extra detail means that setup and analysis take longer in 3D than in 2D. But you're rewarded for that added time with more information; in 3D you can explore mechanisms that just can't be captured in 2D, giving you a better representation of some physical systems.

Once you've created the 3D geometry, you can analyse it in 3D or using many 2D cross sections. Doing so gives you a more spatially representative picture of the stability of your site — which, in the long run, reduces the time required for engineering design and improves the quality of the final design product.

Because 3D modelling is more detailed, it tends to more closely represent the reality of your site. This enables to capture larger and more complex sites in more accurate models. It also makes it easier to use multidisciplinary data to interconnect models across the project life cycle and make more informed decisions. This allows you to combine your data and analysis and build an even more accurate picture of your slope.

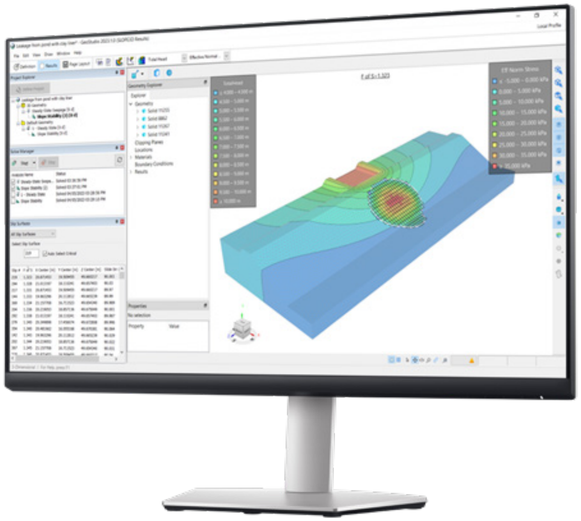
Although 3D modelling takes longer, the right tool can significantly cut down on the time it takes to prepare a model. Look for solutions – like PLAXIS and GeoStudio – that have easy modelling tools, which make it easy to add local fractures, discontinuities and weak planes, as well as loads, displacements, structural elements and reinforcements.

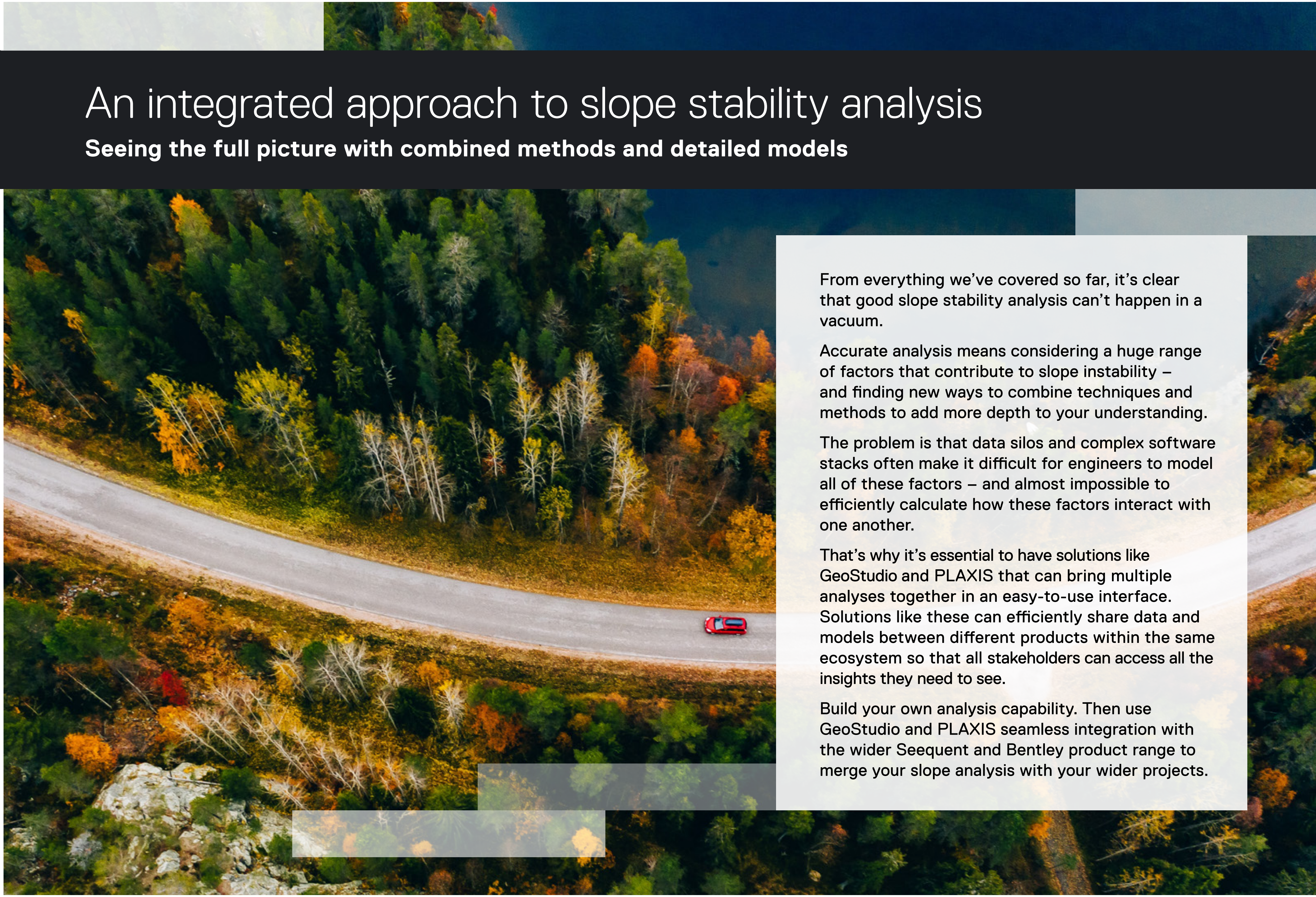
Finding the balance

2D and 3D analysis both have their own benefits, and drawbacks, which make each of them perfect for some situations – and not so perfect for others.

But to find the perfect balance between accuracy and efficiency, most geoscience teams need access to both tools. They need to be able to switch effortlessly between 2D and 3D analysis — feeding the insights gathered from one into the other — as they take on new projects and explore new possibilities.

That's where PLAXIS and GeoStudio come in: They're built to work together, integrating seamlessly to ensure engineers can access the analysis they need, when they need it.





An integrated approach to slope stability analysis

Seeing the full picture with combined methods and detailed models

From everything we've covered so far, it's clear that good slope stability analysis can't happen in a vacuum.

Accurate analysis means considering a huge range of factors that contribute to slope instability – and finding new ways to combine techniques and methods to add more depth to your understanding.

The problem is that data silos and complex software stacks often make it difficult for engineers to model all of these factors – and almost impossible to efficiently calculate how these factors interact with one another.

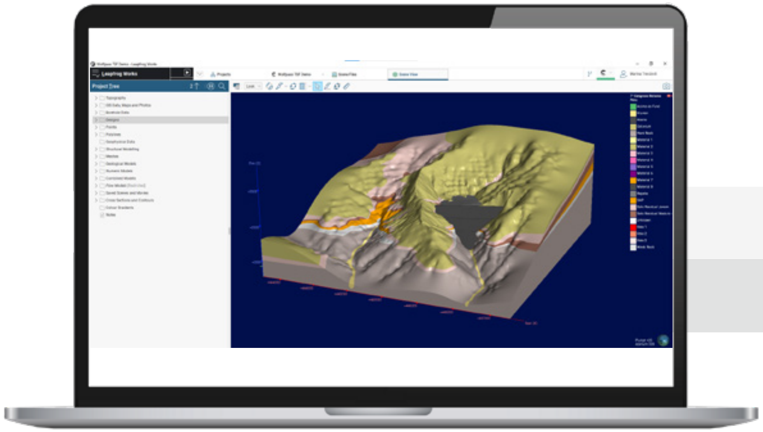
That's why it's essential to have solutions like GeoStudio and PLAXIS that can bring multiple analyses together in an easy-to-use interface. Solutions like these can efficiently share data and models between different products within the same ecosystem so that all stakeholders can access all the insights they need to see.

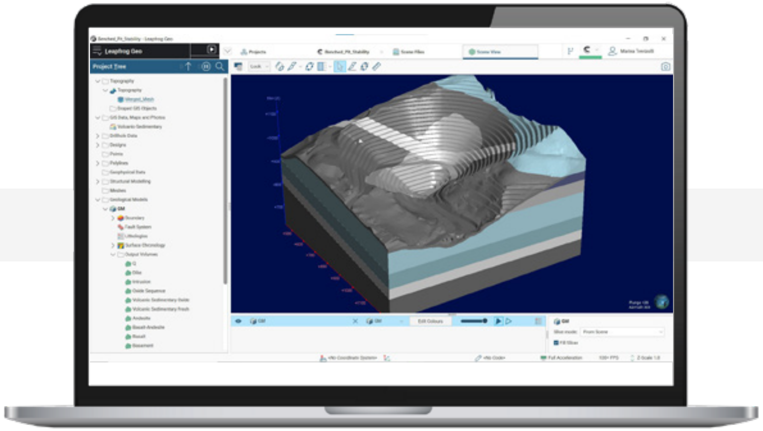
Build your own analysis capability. Then use GeoStudio and PLAXIS seamless integration with the wider Seequent and Bentley product range to merge your slope analysis with your wider projects.

Share, expand, and use your insights effortlessly with Seequent and Bentley products

GeoStudio and PLAXIS are both part of the Seequent and Bentley ecosystem — which makes it easy to integrate any of your slope stability outputs with your wider project workflow.

Not sure where to begin? Start with two of our biggest products:





leapfrog

Leapfrog 3D geological modelling

Leapfrog is a revolutionary solution for understanding, visualising, and communicating ground conditions. It's 3D implicit geological modelling software that allows for quick construction of 3D models from drillhole, GIS, and structural data — with less time spent on manual digitalisation.

How does it integrate?

Use 3D geological models created in Leapfrog to define the 2D or 3D geometry of your analyses in GeoStudio and PLAXIS.

Using this data, you can develop a digital twin of the site that encompasses both the subsurface geological model and the geotechnical analyses. Giving your people the single source of truth they need to make informed decisions.

CENTRAL

Central data management

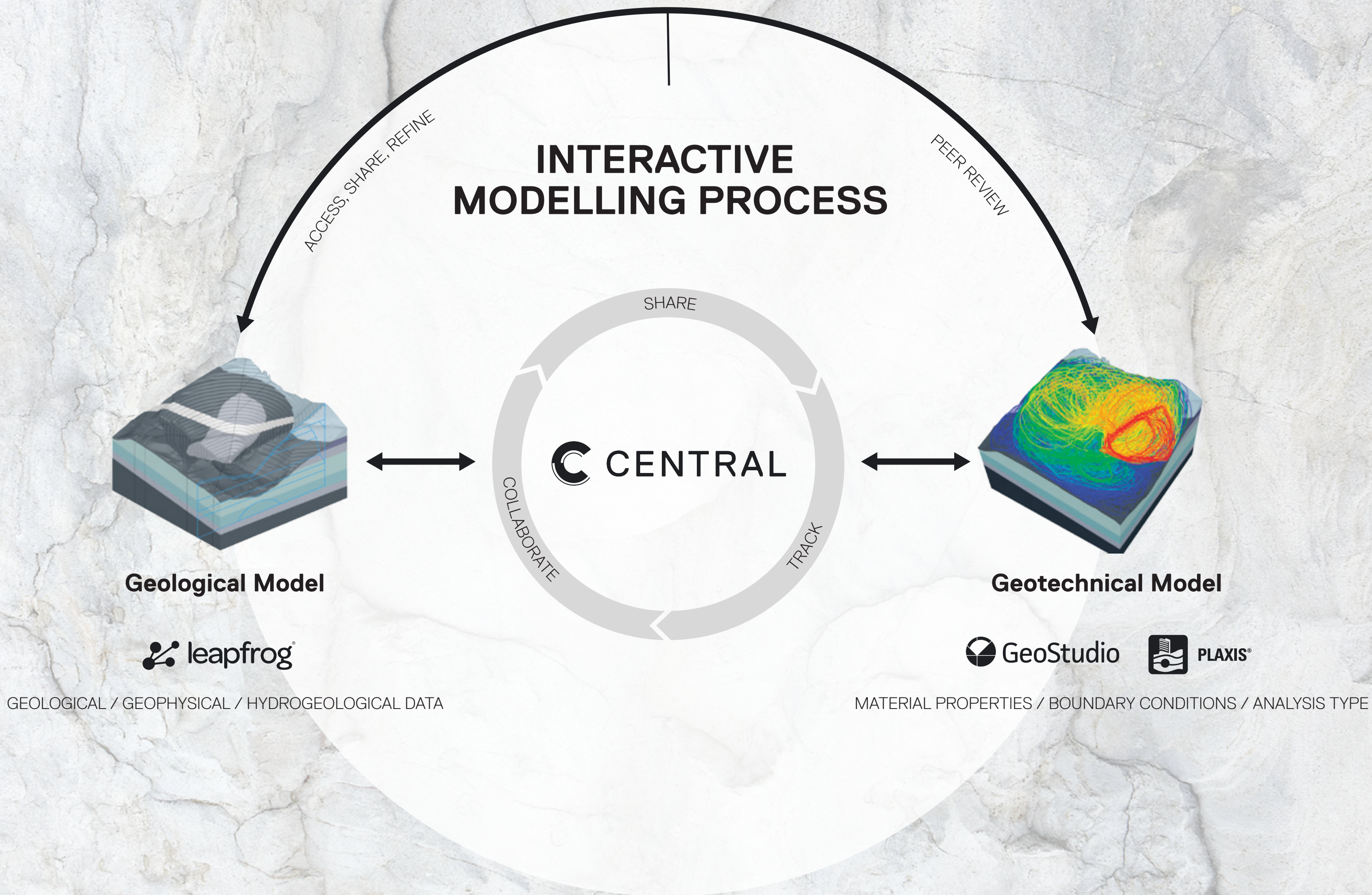
Seequent Central is an enabler of connected workflows, shared 3D visualisation, and team collaboration. Designed for teams managing complex geological data, it sits at the heart of your modelling process, bringing together insights and effective data management within an auditable environment.

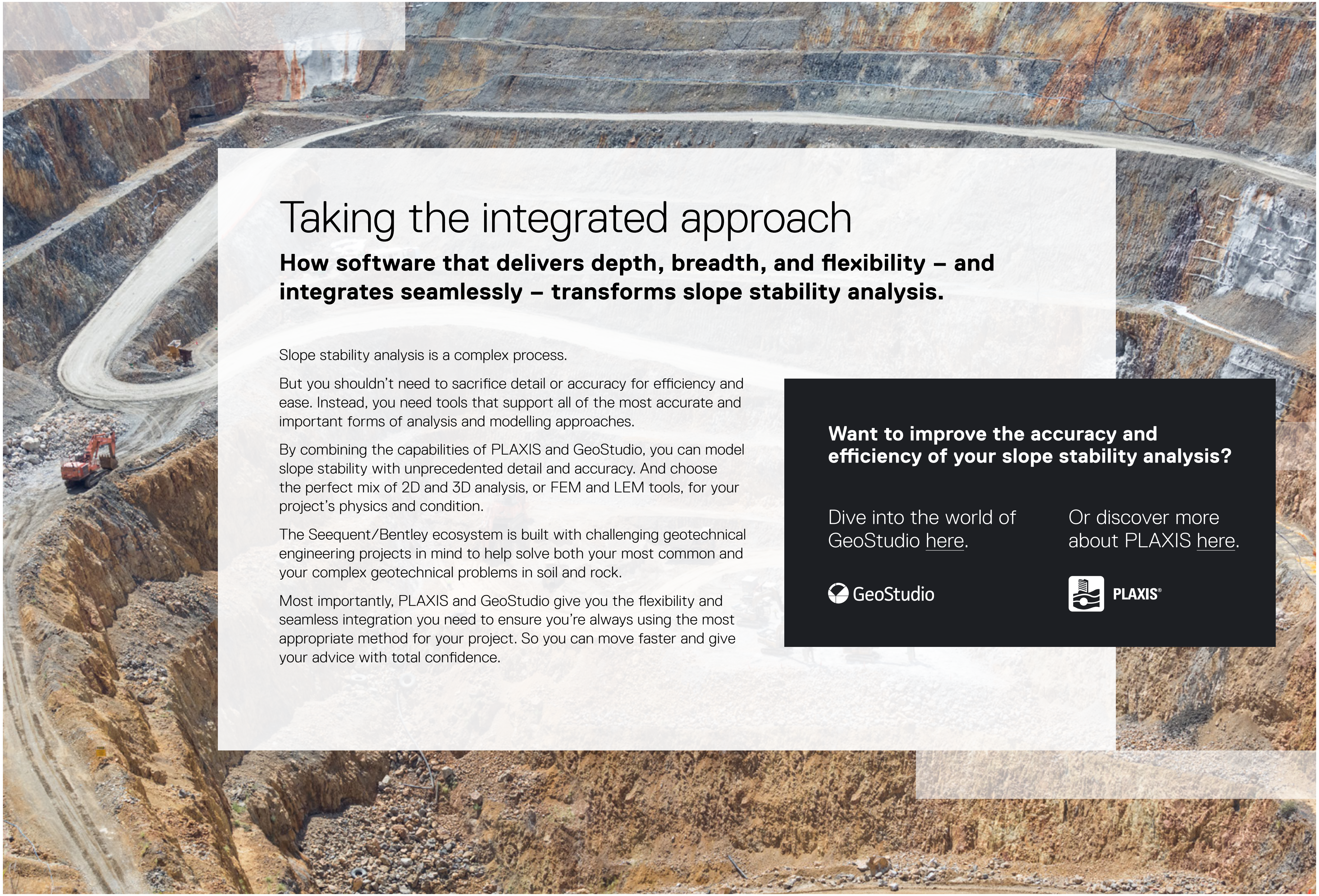
Central is cloud based — meaning your team can work from anywhere and stay constantly up to date on the progress of your projects. Giving them the insights they need to make decisions confidently and efficiently.

How does it integrate?

Import and synchronise published Leapfrog geological cross-sections and surfaces from Seequent Central into PLAXIS and GeoStudio to build out your models. Geological models can also be fully imported into GeoStudio for 3D slope stability analysis.

A Connected Geotechnical Analysis Workflow





Taking the integrated approach

How software that delivers depth, breadth, and flexibility – and integrates seamlessly – transforms slope stability analysis.

Slope stability analysis is a complex process.

But you shouldn't need to sacrifice detail or accuracy for efficiency and ease. Instead, you need tools that support all of the most accurate and important forms of analysis and modelling approaches.

By combining the capabilities of PLAXIS and GeoStudio, you can model slope stability with unprecedented detail and accuracy. And choose the perfect mix of 2D and 3D analysis, or FEM and LEM tools, for your project's physics and condition.

The Seequent/Bentley ecosystem is built with challenging geotechnical engineering projects in mind to help solve both your most common and your complex geotechnical problems in soil and rock.

Most importantly, PLAXIS and GeoStudio give you the flexibility and seamless integration you need to ensure you're always using the most appropriate method for your project. So you can move faster and give your advice with total confidence.

Want to improve the accuracy and efficiency of your slope stability analysis?

Dive into the world of GeoStudio here.

Or discover more about PLAXIS here.

GeoStudio

PLAXIS®

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