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# Numerical Investigation of Rock-Slope Stabilization and the Effect of Young's Modulus on Footing Settlement using PLAXIS 2D

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***Abstract*** **- This study presents two numerical investigations conducted using PLAXIS 2D. The first investigation evaluates the stabilization of a 15 m high road-cut slope in siltstone containing an inclined fault plane. The slope was excavated in stages and supported using prestressed cable anchors, a retaining wall, and toe backfill. The second investigation evaluates the effect of sandy-clay Young's modulus on the settlement of a loaded footing. Five soil-stiffness values—10, 20, 30, 40, and 50 MPa—were analysed while maintaining the same geometry, loading, strength parameters, drainage conditions, and mesh configuration. The footing settlement decreased from 453.90 mm at 10 MPa to 91.68 mm at 50 MPa, representing a 79.8% reduction (59.7% between 20 and 50 MPa). The results demonstrate that soil stiffness substantially influences foundation settlement and that staged support systems are essential for controlling potential fault-related movement in excavated rock slopes. [1]–[3]**

***Keywords*** **- PLAXIS 2D, rock slope stabilization, fault plane, cable anchors, retaining wall, footing settlement, Young's modulus, sandy clay.**

## I. INTRODUCTION

Numerical modelling is widely used in geotechnical engineering to evaluate deformation, settlement, and stability under complex ground conditions [4]. PLAXIS 2D enables the simulation of staged excavation, structural-support installation, soil–structure interaction, and variation in material parameters. In this study, two separate numerical models were developed: a faulted rock-slope stabilization model and a footing-settlement model on sandy clay.

The first model examines a road-cut slope formed in siltstone and intersected by a weak fault plane. Because the fault dips towards the excavated face and reaches the toe region, it represents a potential sliding surface after excavation. The model therefore incorporates staged cable installation, a retaining wall, and backfill as stabilization measures. [1], [2]

The second model investigates the influence of Young's modulus on settlement beneath a uniformly loaded footing. Soil Young's modulus governs the stiffness response of the foundation soil and strongly affects the magnitude of vertical deformation. The study compares settlement behaviour for five Young's modulus values ranging from 10 MPa to 50 MPa. [3]

Finite-element analysis has been used for slope stability assessment and for footing settlement prediction because it accounts for the actual stress–strain response of the ground without prescribing the shape of the failure surface in advance [5]. This makes it suitable for faulted rock masses, where failure is controlled by a discontinuity, and for foundations on soils whose stiffness is uncertain.

## II. OBJECTIVES

The objectives of this study were:

1. To model a staged road-cut excavation in faulted siltstone using PLAXIS 2D.
2. To evaluate a slope-stabilization arrangement consisting of prestressed cables, a retaining wall, and backfill.
3. To develop a footing-settlement model for sandy clay under a vertical load.
4. To investigate the effect of Young's modulus on the maximum settlement beneath the footing.
5. To compare settlement values for soil Young's modulus values of 10, 20, 30, 40, and 50 MPa.

## III. METHODOLOGY

### *A. Numerical Modelling Approach*



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Both analyses were performed in PLAXIS 2D under plane-strain conditions using 15-noded triangular elements. The models were developed to represent realistic staged construction and loading conditions. Material models were selected according to the behaviour of the rock mass, fault plane, soil, and structural elements.

The rock slope was represented using the Hoek–Brown rock-mass model, while the fault and sandy clay were modelled using the Mohr–Coulomb model. The footing and retaining-wall elements were represented as linear-elastic structural components. [1]–[3]

The Hoek–Brown criterion estimates rock-mass strength from the intact uniaxial compressive strength, the material constant $m_i$, the Geological Strength Index (GSI), and the disturbance factor D [6], [7]. The Mohr–Coulomb model is defined by the stiffness, Poisson's ratio, cohesion, friction angle, and dilatancy angle of the soil [4].

## IV. ROCK-SLOPE STABILIZATION ANALYSIS

### *A. Geometry of the Rock Slope*

The rock-slope model consisted of a 15 m high road cut. The numerical domain extended from 0 m to 45 m horizontally and from −13 m to 15 m vertically. Excavation was carried out in two stages: an initial 9 m excavation followed by a further 6 m excavation. [1]

A fault plane dipping at 38.7° was incorporated into the model. The fault extended from approximately (8 m, 15 m) to (42 m, −13 m). It was located approximately 12 m behind the slope crest and intersected the slope-toe region. Its orientation and weak mechanical properties made it the principal potential surface for slope movement. [1], [2]

### *B. Rock-Mass Properties*

The slope consisted of siltstone represented using the drained Hoek–Brown model. The principal rock-mass parameters used in the analysis are presented in Table I.

TABLE I — ROCK-MASS PROPERTIES OF SILTSTONE

| Parameter | Value |
|---|---|
| Material | Siltstone |
| Unit weight | 24 kN/m3 |
| Young's modulus | 1.0 × 10⁶ kN/mZ |
| Poisson's ratio | 0.25 |
| Intact uniaxial compressive strength | 25 × 103 kN/mZ |
| Material constant, $m_i$ | 10 |
| Geological Strength Index | 39 |
| Disturbance factor | 0 |
| Tensile strength | 30 kN/mZ |
| Dilatancy angle | 10° |

Source: [1].

### *C. Fault Properties*

The fault was represented as a drained Mohr–Coulomb discontinuity. A normal stiffness of 1.0 × 10⁶ kN/m3 and shear stiffness of 100 × 103 kN/m3 were assigned. The fault had a cohesion of 8 kN/mZ, friction angle of 20°, and zero dilatancy. These values reflect the comparatively weak nature of the fault relative to the surrounding siltstone. [1] The fault parameters are summarised in Table II.

TABLE II — FAULT PARAMETERS

| Fault parameter | Value |
|---|---|
| Normal stiffness | 1.0 × 10⁶ kN/m3 |
| Shear stiffness | 100 × 103 kN/m3 |
| Cohesion | 8 kN/mZ |
| Friction angle | 20° |
| Dilatancy angle | 0° |

### *D. Stabilization System*

The slope-stabilization system included three rows of 25.4 mm prestressed cable anchors installed at 3 m spacing. Each cable had a tensile yield capacity of 548 kN and was prestressed to 200 kN. [1]

A reinforced-concrete retaining wall was constructed at the toe of the slope. The wall was 3 m high and 1 m thick. Backfill was subsequently placed between the retaining wall and the excavated slope face to provide additional toe restraint. [1]

In a finite-element model, prestressed anchors act on the rock mass through the applied prestress force, which counteracts the driving shear stress along the potential sliding surface and increases the normal stress acting on the fault [8]. Each anchor was therefore prestressed to 200 kN, which is about 36% of its 548 kN yield capacity.

### *E. Construction Sequence*

The construction sequence used in the slope model was:

1. Generation of the initial in-situ stress condition.
2. Excavation of the upper 9 m portion of the road cut.
3. Installation of the first and second rows of prestressed cable anchors.
4. Excavation of the remaining 6 m of the slope.
5. Installation of the third cable row.
6. Construction of the retaining wall at the toe.
7. Placement of backfill behind the retaining wall.
8. Safety analysis after the final excavation and after backfilling.

[1], [2]

### *F. Discussion of Slope Behaviour*

The fault orientation creates a potentially unstable condition because the discontinuity dips towards the excavated slope face. Staged excavation can reduce lateral confinement and mobilize shear stresses along the fault. The cable anchors provide reinforcement across the potential sliding zone, while the retaining wall and backfill enhance toe support. [1], [2]

The available model information describes the geometry, materials, support measures, and calculation stages; however, numerical values for the final safety factor and slope displacement were not reported. Therefore, the slope analysis should be interpreted as a stabilization-model study rather than a quantified comparison of unsupported and supported safety factors.

In PLAXIS 2D, the safety factor is normally obtained from a



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safety (strength-reduction) analysis, in which the strength parameters are progressively reduced until failure occurs [4], [5]. Reporting the safety factor and the maximum displacement for the unsupported and supported cases is therefore recommended in subsequent work.

## V. FOOTING SETTLEMENT ANALYSIS

### *A. Model Geometry and Loading*

The footing-settlement model consisted of a soil domain 20 m wide and 10 m deep. The footing had an approximate width of 1.5 m and was embedded at a depth of approximately 1.0 m. A uniform vertical load of 1000 kN was applied to the footing. [3]

The footing was modelled as a linear-elastic concrete element with a Young's modulus of 25 GPa, Poisson's ratio of 0.20, and unit weight of 25 kN/m3. [3]

### *B. Soil Properties*

The foundation soil was sandy clay modelled using the drained Mohr–Coulomb model. The adopted parameters are shown in Table III.

TABLE III — SANDY-CLAY SOIL PARAMETERS

| Soil parameter | Value |
|---|---|
| Soil type | Sandy clay |
| Unsaturated unit weight | 16.0 kN/m3 |
| Saturated unit weight | 17.8 kN/m3 |
| Poisson's ratio | 0.30 |
| Effective cohesion | 15.2 kN/mZ |
| Effective friction angle | 20° |
| Dilatancy angle | 0° |
| Drainage condition | Drained |

Source: [3].

The groundwater level was assumed to be below the base of the model. Standard boundary conditions were applied, with the base restrained in both directions and the vertical boundaries restrained horizontally. [3]

### *C. Calculation Phases*

The settlement analysis consisted of two main phases:

1. Initial stress generation using the $K_0$ procedure.
2. Activation of the footing and application of the vertical load in a plastic calculation phase.

A medium triangular mesh was used for all cases. Only the reference Young's modulus of the sandy clay was varied; all other parameters, including geometry, load, strength properties, drainage condition, and mesh density, were maintained constant. [3]

## VI. RESULTS: EFFECT OF YOUNG'S MODULUS ON SETTLEMENT

Five Young's modulus values were considered: 10, 20, 30, 40, and 50 MPa. The reported settlement corresponds to the maximum downward vertical displacement beneath the footing. [3] The results are given in Table IV and plotted in Fig. 1.

TABLE IV — EFFECT OF YOUNG'S MODULUS ON MAXIMUM SETTLEMENT

| Young's modulus, E′ref | Maximum settlement | Reduction relative to 10 MPa |
|---|---|---|
| 10 MPa | 453.90 mm | 0.0% |
| 20 MPa | 227.70 mm | 49.8% |
| 30 MPa | 152.70 mm | 66.4% |
| 40 MPa | 114.60 mm | 74.8% |
| 50 MPa | 91.68 mm | 79.8% |

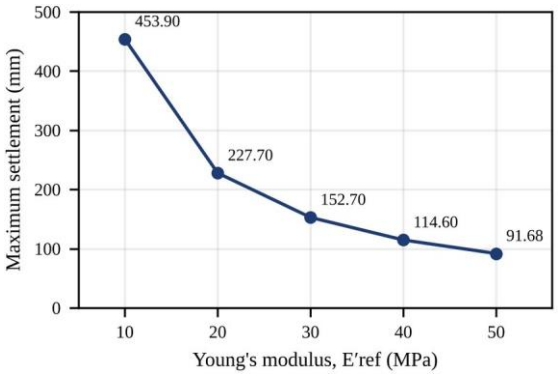


*Fig. 1. Maximum footing settlement versus Young's modulus of sandy clay (data from Table IV).*

The results show a clear inverse relationship between Young's modulus and settlement. When Young's modulus increased from 10 MPa to 50 MPa, the maximum settlement reduced from 453.90 mm to 91.68 mm. This corresponds to a total settlement reduction of 362.22 mm, or approximately 79.8%. Over the 20–50 MPa range alone, the reduction was 136.02 mm, or approximately 59.7%. [3]

The largest absolute reduction occurred between 10 MPa and 20 MPa, where settlement decreased by 226.20 mm (49.8%). Between 20 MPa and 30 MPa, settlement decreased by 75.00 mm. Increasing Young's modulus from 30 MPa to 40 MPa reduced settlement by 38.10 mm, while the increase from 40 MPa to 50 MPa reduced settlement by 22.92 mm. Thus, the rate of settlement reduction decreased as soil stiffness increased. [3]

TABLE V — SETTLEMENT REDUCTION PER INCREMENT OF YOUNG'S MODULUS

| Increase in Young's modulus | Settlement reduction |
|---|---|
| 10 MPa to 20 MPa | 226.20 mm |
| 20 MPa to 30 MPa | 75.00 mm |
| 30 MPa to 40 MPa | 38.10 mm |
| 40 MPa to 50 MPa | 22.92 mm |

The maximum upward displacement elsewhere in the numerical model also reduced with increasing Young's modulus, decreasing from 5.25 mm at 20 MPa to 2.35 mm at 50 MPa. The results indicate that the settlement response was approximately inversely proportional to Young's modulus within the analysed range. [3]

This proportionality can be checked directly from Table IV: the product of Young's modulus and maximum settlement is 4539 MPa·mm at 10 MPa, 4554 MPa·mm at 20 MPa, 4581 MPa·mm at 30 MPa, and 4584 MPa·mm at both 40 MPa and



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50 MPa, i.e. constant to within about 1%. This agrees with foundation, $s = qBI(1 - \nu Z)/E$, in which settlement varies with 1/E for a given load, geometry, and Poisson's ratio [9], [10]. The near-constant product suggests that the response was dominated by elastic deformation, with the plastic contribution being small in the range investigated.

## VII. DISCUSSION

The footing analysis confirms that Young's modulus is a key parameter for predicting foundation settlement. At lower stiffness values, the sandy clay experienced larger vertical deformation under the applied 1000 kN footing load. Increasing the Young's modulus enhanced the soil's resistance to compression and reduced the resulting settlement. [3]

The reduction in settlement was largest when soil stiffness increased from 10 MPa to 20 MPa (226.20 mm), and it remained substantial from 20 MPa to 30 MPa. However, the additional settlement reduction became smaller at higher stiffness values. This trend indicates diminishing benefits from further increases in Young's modulus within the investigated range. [3]

For the rock-slope case, stabilization was designed to address potential movement along the inclined fault plane. The use of prestressed cable anchors helps transfer stabilizing forces across the weak discontinuity, while the retaining wall and backfill improve toe confinement. The staged installation of support during excavation is important because it provides restraint before the full 15 m cut is completed. [1], [2]

Taken together, the two investigations show that deformation and stability outcomes in PLAXIS 2D depend on the correct selection of constitutive parameters. For the foundation, Young's modulus should be determined from field or laboratory testing, since a small error in stiffness produces a proportionally large error in the predicted settlement [9].

## VIII. CONCLUSIONS

1. A 15 m high siltstone road cut containing a 38.7° fault plane was modelled in PLAXIS 2D using staged excavation. The fault intersects the toe region and represents the principal potential sliding surface. [1], [2]
2. The slope-stabilization system consisted of three rows of prestressed cable anchors, each prestressed to 200 kN, together with a 3 m high and 1 m thick retaining wall and toe backfill. [1], [2]
3. The footing-settlement analysis demonstrated that settlement decreases as sandy-clay Young's modulus increases. The maximum settlement was 453.90 mm at 10 MPa, 227.70 mm at 20 MPa, and 91.68 mm at 50 MPa. [3]
4. Increasing Young's modulus from 10 MPa to 50 MPa produced a 79.8% reduction in maximum footing settlement (59.7% between 20 MPa and 50 MPa). [3]
5. The largest reduction in settlement occurred when Young's modulus increased from 10 MPa to 20 MPa the linear-elastic expression for the settlement of a shallow (226.20 mm), followed by 75.00 mm from 20 MPa to 30 MPa. Further increases in stiffness continued to reduce settlement, but with progressively smaller incremental benefits. [3]
6. Reliable determination of Young's modulus is essential for realistic settlement prediction. Ground-improvement methods that increase soil stiffness may be effective for reducing settlement where low-stiffness sandy clay is present. [3]

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