Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-191

Numerical analysis of an unstable slope

Analyse numérique d'une pente instable

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ABSTRACT: A slope adjacent to a northbound regional motorway, outside the city of Barcelona, has shown signs of instability, which have affected the functionality of the road. An extensive instrumentation system has allowed to observe the movement of the slope and locate the slip surface in various sections. The paper presents the study of the instability phenomenon and its origin by means of 2D numerical analyses. Monitoring data has been used to validate the numerical model and to reproduce the observed slope behaviour. In the present work, the features of the numerical study are described and the results are then compared with the in-situ observations.

RÉSUMÉ: Une pente adjacente à une autoroute régionale en direction nord, à l'extérieur de la ville de Barcelone, a montré des signes d'instabilité qui ont affecté la fonctionnalité de la route. Un vaste système d'instrumentation a permis d'observer le mouvement de la pente et de localiser la surface de glissement dans différentes sections. L'article présente l'étude du phénomène d'instabilité et de son origine au moyen d'analyses numériques 2D. Les données de surveillance ont été utilisées pour valider le modèle numérique et reproduire le comportement de pente observé. Dans le présent travail, les caractéristiques de l'étude numérique sont décrites et les résultats sont ensuite comparés aux observations in situ.

Keywords: Slope analysis; numerical modelling; monitoring; stabilizing measures.

1 INTRODUCTION

Instability phenomena on natural and cut slopes are, in general, highly complex phenomena that must be properly identified to select appropriate stabilising measures (Alonso, 2021, Argyroudis et al., 2019). An incorrect estimation of these phenomena can lead to the adoption of ineffective or even counterproductive solutions for their stabilisation (Corominas, 2006).

Road networks are often exposed to the instability phenomena of nearby slopes, with the consequent impact on their users, as well as on the same transport infrastructures. Identifying problematic areas and managing the associated risks represent a priority to guarantee both the functionality and safety of road networks (Mavrouli et al. 2019).

The present work summarises the results of a 2D numerical finite element (FE) analysis carried out to study the stability of a slope adjacent to a road north of the city of Barcelona. Slope monitoring has provided detailed information on the instability mechanism and the location of the slip surface. The numerical results are compared with in-situ observations.

2 DESCRIPTION OF THE CASE STUDY

The slope object of this study borders a motorway whose construction dates back to the late 1980's. On the upper part of the slope an old quarry is present, the exploitation of which lasted a little over 40 years, from around 1960 to 2004 (Fig. 1). The materials extracted from the quarry were dolomites and limestones used mostly in the construction industry.

To reduce the environmental impact of the quarry and prevent the degradation of the slope, restoration measures were implemented once the activity of the quarry ended. The open-pit mine was hence converted into a construction and demolition waste (CDW) disposal deposit. A few years after the slope restoration began, a number of anomalies and defects signs repeatedly appeared on the pavement of the motorway, at the toe of the slope (Di Mariano and Gens, 2023).

The first study to determine the origin of the pavement's faults was carried out in 2008 and some corrective measures were implemented along the toe of the slope. At that time, the road deficiencies were attributed to the possible presence of expansive materials below the pavement of the road. The implemented corrective measures, which included the construction of a gabion wall (Fig. 1), were nevertheless inadequate to definitely recover the road safety and functionality. Later on, in 2017, when significant repair works were being executed, the Contractor was able to relate the road deformation signs exclusively to the movement of its adjacent slope. An extensive monitoring plan was hence deployed to keep track of the slope instability phenomenon and properly define its limits.

Figure 1. Layout of the motorway and the old quarry on the upper part of the slope (right-hand side). The picture also shows the industrial estate on the opposite side of the road with respect to the unstable slope (discontinuous line) and the location of Section G object of this study (Google maps image).

2.1 Geological Conditions

The lithological sequence of the slope in the area under study includes the materials listed in Table 1, from the most recent (RC) to the oldest (BC).

According to the latest available data, the failure surface of the slope is located at a depth of about 40 m, mainly placed within the shales layer (unit BC in Fig. 2), the upper part of which appears strongly weathered. During the exploitation of the old quarry, the excavation of the upper quaternary materials left the underlying shales layer exposed to atmospheric agents in many parts of the slope, probably favouring its weathering. When the restoration process began and the quarry was converted into a CDW disposal deposit, the hydraulic conditions of the slope changed mainly due to the fact that the base of the deposit was waterproofed.

The unstable slope directly affects the regional motorway, as well as nearly the entire old quarry location (Figs 1-2). It also indirectly affects the bed of a river located downhill from the motorway, an industrial estate located between the motorway and the river, as well as some telecommunications and electrical supply lines (Di Mariano et al., 2022).

Table 1. Lithological sequence of the slope under study.

Material	USCS	Description
RC	-	Construction waste materials
R	-	Anthropic fills
E	Not available	Eocene siltstones and sands
Q	GC	Sandy clays with gravel from the Quaternary Era
M*	CL	Alternation of dolomitic and calcareous rocks from the Middle Triassic
BC	SC, CL	Shale, claystone and sandstone deposits from the Lower Triassic

*(materials exploited in the old quarry)

2.2 Field Instrumentation

The motorway, its adjacent slope and the waste deposit, including their surroundings, are extensively instrumented. The monitoring system comprises topographic and geotechnical devices to control the evolution of both surface and subsurface ground movement, as well as to locate the slope slip surface (Figs 1-2 show all biaxial inclinometers, I, in section G). Topographic surveys include both geometric and GPS (Global Positioning System) levelling. Field monitoring also consists of open standpipes and vibrating wire piezometers (indicated as PZ in Fig. 2) to observe variations in the water table and pore water pressure evolution at the slip surface, respectively.

The main purpose of this extensive monitoring plan was to identify the origin of the slope instability. The observed movements indicated that the slope was indeed moving and that the depth of the slip surface was about 40 m (Fig. 2).

2.3 Origin of the instability and corrective measures

The removal of dolomitic and calcareous rocks from the head of the slope caused a gradual increase in the slope Safety Factor (SF), which decreased during the construction of the motorway, almost 30 years later, due to the cut made at the slope's toe. Later, when the old quarry was converted into a waste deposit, the head of the slope was loaded with time, producing a further and progressive decrease in its SF that eventually led to the instability of the slope when the restoration process was almost completed.

Once the origin of the problem in the motorway was identified, the Contractor performed some numerical analyses to study the effect of possible corrective measures on the stabilisation of the slope. Different measures such as the construction of diaphragm walls as a reinforcement at the road level or the application of a ground load at the toe of the slope, with the consequent diversion of the river on the other side of the slope or the removal of the waste material at the head of the slope were considered. Among all of them, the latter was selected as the most appropriate in terms of environmental impact, flexibility, cost and time of execution. The unloading of the head of the slope began in 2018 and continued until February of 2022.

The slope movement rate varied over time with both the hydraulic conditions and the excavated volume of waste material. As soon as the unloading process started, the rate of the slope movement decreased, even though at the beginning it was yet quite sensitive to changes in pore water pressures. As the removal of waste material continuously reduced the driving forces on the slide, the movement became progressively slower. Currently, with the unloading process yet to be completed, the movement rate is approximately 0.3 mm/month.

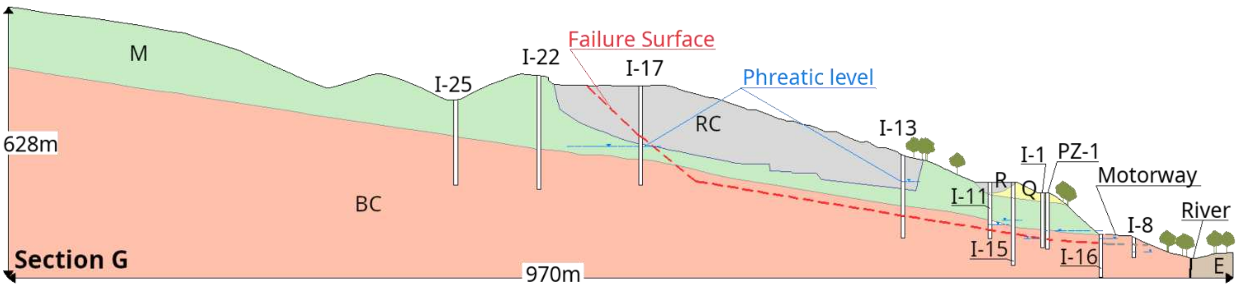

Figure 2. Geological profile along Section G of the slope. The failure surface observed through the inclinometer readings is indicated in red.

3 NUMERICAL MODEL

With all available data and information, the authors of the paper carried out new FE numerical analyses, with the commercial code PLAXIS 2D, to analyse the instability phenomenon in detail and reproduce the observed slope movement as well as the shape and dimensions of the observed slip surface.

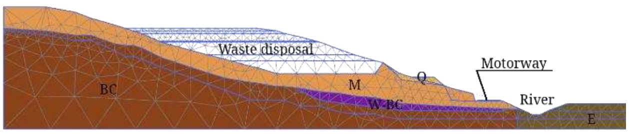

Figure 3. Detail of the FE mesh of the 2D numerical model.

Three different constitutive models were used to represent the ground materials behaviour, with the objective to analyse their influence on the movements distribution along the slope; the generalised Hoek-Brown criterion to account for the different weathering degrees of the rock masses (Hoek-Brown), a simple linear elastic perfectly plastic constitutive model (Mohr-Coulomb) and, finally, an advanced non-linear elastoplastic model with hardening plasticity (HS). The last two models are based on the Mohr-Coulomb failure criterion. In all numerical analyses, the hydraulic conditions approximately reproduce the evolution of the water table with time. Boundary conditions were standards, with a fixed lower boundary and the lateral ones allowing only vertical displacements. No restrictions were imposed on the top boundary.

At first, all numerical analyses were run with the numerical model shown in Figure 3, using the three previously mentioned constitutive models with equal, or equivalent, strength and stiffness parameters. The observed slope movement at inclinometer I-13 (Figs 1-2) and the numerical results associated to different constitutive laws are shown in Figure 4.

Table 2. Strength and stiffness parameters of the M, BC and W-BC deposits for the HS constitutive model.

Layer	c′ (kPa)	φ′ (º)	E_{50} (MPa)	E_{oed} (MPa)	E_{ur} (MPa)
M	20	30	1426	1069	2994
BC	33	38	8750	6560	18375
W-BC	0	18	10	7.5	21

The geomechanical parameters that characterize each ground layer were evaluated based on several laboratory and in situ tests. In Figure 3, the thin layer indicated with the symbol W-BC represents the upper weathered part of the BC deposit, identified from the boreholes, and along which part of the failure surface is located. This layer in the model is characterised by residual strength parameters and much lower stiffness values than those of the unweathered BC materials (Table 2). Such stiffness values were estimated from back-analysis. Table 2 contains the ground effective strength and stiffness parameters corresponding to the

HS constitutive model. As Figure 4 indicates, the HS model proved to be the one that best reproduces the slope horizontal movement with depth, confirming thus that it is indeed important to consider the strong non-linearity of ground materials. Also, in this case study, the unloading-reloading stiffness modulus (E_{UR}) plays a key role in characterising the ground behaviour; more relevant than the oedometric (E_{oed}) or secant modulus in drained triaxial tests (E_{50}).

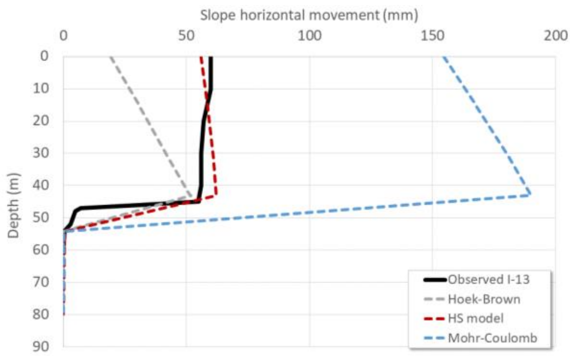

Figure 4. Observed horizontal movement with depth, at inclinometer I-13 and numerical results obtained with different constitutive models.

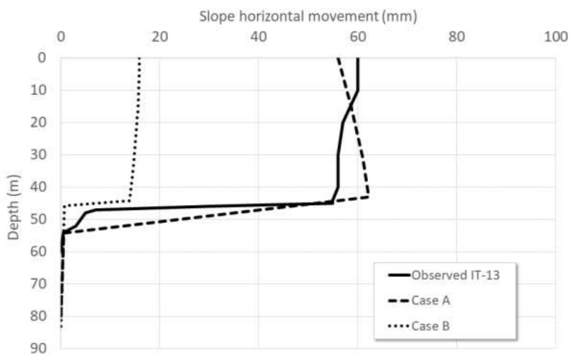

Figure 5. Observed horizontal movement, at inclinometer I-13 and numerical results, considering different slip surface thicknesses and the same HS constitutive model.

According to the different inclinometer readings, the thickness of the slip surface is not uniform throughout the slope, in general being thicker (up to about 10 m) further away from the motorway, as it is approximately represented by the varying thickness of the W-BC layer in Figure 3. In a second phase of this study, two different numerical models (both calculated with the HS model) were considered, each with a different thickness of the W-BC layer, in order to analyse how this feature affects the numerical results. Figure 5 shows the comparison between the observed slope horizontal movement, at inclinometer I-13, and the numerical results in two different scenarios: case (A), in which the thickness of the W-BC layer varies along the slope (Fig. 3) and case (B), in which the same layer has a uniform 2 m thickness. The results show that the thickness of this layer greatly affects the results and, in general, the movement of the slope.

4 SUMMARY AND CONCLUSIONS

The paper presents a case study about the instability phenomenon affecting a slope adjacent to a motorway connecting the city of Barcelona to the northern part of the Catalan region. To analyse the phenomenon and reproduce the slope movement as well as the observed failure surface, 2D finite element numerical analyses were carried out using different constitutive laws.

Considering the non-linearity of ground behaviour in elastoplastic models is crucial to reproduce the observed slope movement. The shape of the slip surface, as it is recorded by inclinometer readings, could only be adequately replicated considering the weathering of the shale deposits from the Lower Triassic. Ground movement distribution is strongly affected by the thickness of the failure surface.

ACKNOWLEDGEMENTS

The authors are grateful for the data and financial support provided by Infraestructures.cat.

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