# Three-dimensional numerical simulation of the dynamic behavior of slopes of the Costa Verde cliff - Armendariz Sector

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**Abstract.** In this research, slope stability was evaluated in dynamic terms, specifically in the Armendariz descent, by means of three-dimensional numerical analysis using the finite element technique and finite differences, where the parameters were calibrated for static and dynamic conditions by means of large-scale tests and wave propagation, respectively. For the estimation of the parameters under static conditions, the elastic-plastic response trajectory of the large-scale direct shear test was taken into account and compared with the numerical model with the same test characteristics until the soil parameters were found by curve fitting (comparison with the response of the in-situ test). For the estimation of the parameters under dynamic conditions, comparisons were made between the dynamic responses, in terms of accelerations, recorded instrumentally with the three-dimensional dynamic wave propagation analysis, considering the soil stratigraphy and the geometric configuration of the slopes.

**Keywords:** Dynamic Analysis, Three-Dimensional Numerical Analysis, Slope Stability Analysis

## 1 Introduction

Currently, research on slope stability analysis carried out on the green coast (Cañari, 2002; Macazana, 2006; Raygada, 2011) has considered two-dimensional geometric analysis criteria, which would not be a good approximation because the geomorphology is irregular and the buildings produce irregular lateral effects. On the other hand, the dynamic evaluation is performed by means of the pseudo-static approach, which is limited in terms of definition of the equivalent seismic force, being its use of conservative character, additionally this methodology does not allow the estimation of the deformations by earthquake and the use of the seismic record in all its magnitude, i.e. the variation of the accelerations during the occurrence of the earthquake.

The purpose of this research is to show the analysis of the three-dimensional dynamic numerical simulation of the slopes of the Costa Verde cliff - Armendariz sector, using the finite element technique and finite differences.

## 2 Development

### 2.1 Hypothesis

The purpose of the research is to show that the three-dimensional dynamic numerical simulation, associated with the estimation of static and dynamic parameters through calibration with in-situ tests, allows to evaluate the dynamic behavior considering the variability of the lateral effects of the slopes of the green coast - Armendariz sector.

## 2.2 Methodology

### 2.2.1 Seismic hazard of the site

The present work will simulate the slopes of the Costa Verde cliff, located in the city of Lima, on the central coast of Peru, whose seismic environment is strongly dominated by the interaction between the Nazca Plate and the South American Plate, where interface subduction seismic events occur, mainly between the limits of the shallowest contact of the tectonic plates and the coastal coastline.

The study area is mainly influenced by the interface subduction events, indicating in turn that there is a considerable contribution of shallow intraplate events given the location of the study area.

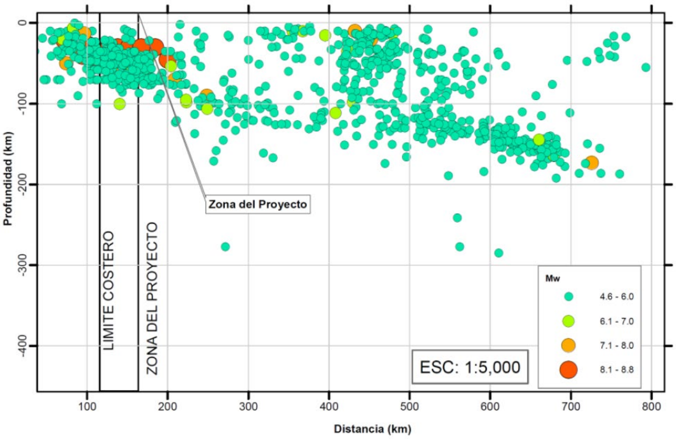

Figure 1. Spatial distribution of instrumental earthquakes.

Figure 1, obtained from the seismic hazard study of the Malecón de la Reserva tourism corridor project in October 2020, shows that the spatial distribution of instrumental earthquakes indicates a greater seismic activity of the subduction zone on the coast. The subduction of the Nazca Plate and its constant friction due to contact with the South American Plate generates interface and intraplate earthquakes, whose focal depths increase following the dip of the contact. The study area is influenced by a superficial subduction with an approximate angle of 21° in the interface zone up to an average depth of 100 km, then the inclination of the subduction of the Nazca plate under the South American plate becomes sub horizontal reaching a depth of 125 km and then slightly increasing its dip to an angle of 15°.

According to the seismic history of the study region, it is concluded that in the last 465 years there have been earthquakes with intensities of up to IX-X (MMI) in the project area and vicinity as shown in the distribution map of maximum seismic intensities (INDECI, 2003), which is consistent with Alva et al. 1984.

Thus, for the seismic characterization of the present investigation, it was evaluated for a return period of 475 years, after which the uniform hazard spectrum associated with the project was analyzed, as shown below.

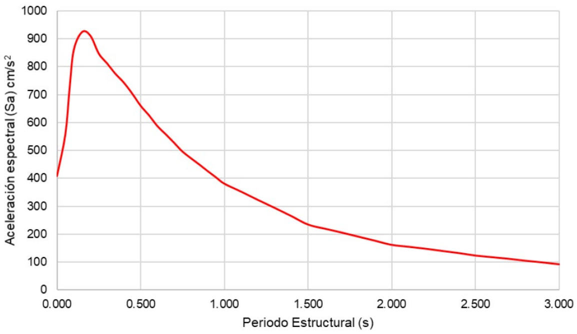

Figure 2. Uniform hazard spectrum, Soil Type B, Tr = 475 years.

Based on the probabilistic seismic hazard disaggregation (Bazurro & Cornel, 1999) and the distribution of characteristic events of the study area, the dominant events of the study area were identified, for which 6 events of similar characteristics were selected, interface and intraplate earthquakes of moment magnitudes greater than or equal to 8. 0, listed in Table 1, for the generation of synthetic events adjusted to a return period spectrum of 475 years, in accordance with the stipulations of AASHTO 2014 and other regulations (U.S. Department of Transportation Federal Highway Administration, 2009).

Table 1. Seismic parameter used

| **Name** | **Date** | **Longitude** | **Latitude** | **Depth (km)** | **Mw** |
|---|---|---|---|---|---|
| | | (°) | (°) | | |
| Lima | 03/10/1974 | -77.98 | -12.5 | 13 | 8.1 |
| Atico | 23/06/2001 | -73.77 | -16.08 | 33 | 8.4 |
| Pisco | 15/08/2007 | -76.60 | -13.39 | 39 | 8.0 |

Spectral fitting was performed with 6 input earthquake records, both NS and EW directions were used:

- Lima 1974, from IGP
- Ático 2001, from CISMID
- Pisco 2007, from CISMID

The logs were baseline corrected from a linear function with the Seismosignal software and then filtered with the Butterworth-Bandpass method, whose filtering parameters are shown below:

| n | F1 | F2 |
|---|---|---|
| 4 | 0.25 | 25 |

n: Filter order.
F1: Lower filtering frequency
F2: Upper filtering frequency

The Fourier spectrum and the time-history record of the corrected ATICO 2001 earthquake are shown as an example.

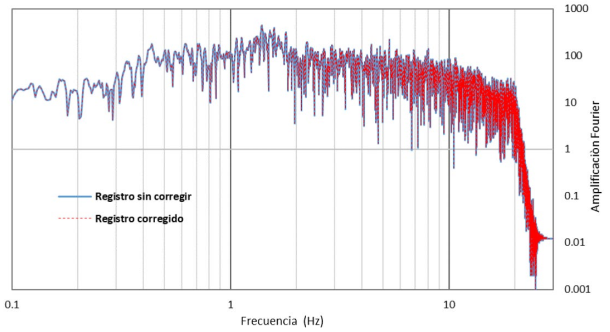

Figure 3.- Fourier spectrum of uncorrected and unfiltered log and corrected and filtered log

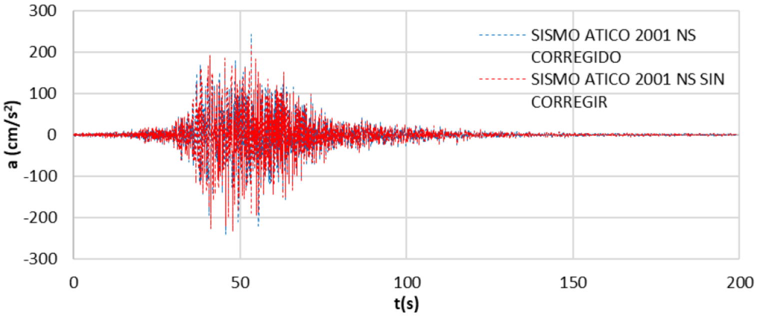

Figure 4.- Time-history graph of log without correction and filtering and log with correction and filtering. (Earthquake ATICO 2001 NS)

To perform the spectral adjustment of the accelerograms of the seismic record in the time domain, the Seismo Match program was used, taking care not to significantly alter the properties of the records that serve as input for the process.

This program performs the spectral adjustment through the use of "Wavelets" (Hancock, et al., 2006) in such a way that the adjusted response spectrum is assimilated to the uniform hazard spectrum. As an example, the adjustment of the 2001 NS Attic earthquake is shown.

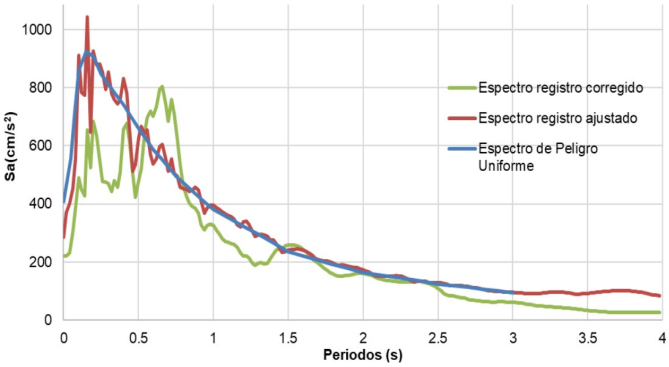

Figure 5.- Response spectrum of the corrected (unadjusted) and spectrally adjusted recording.

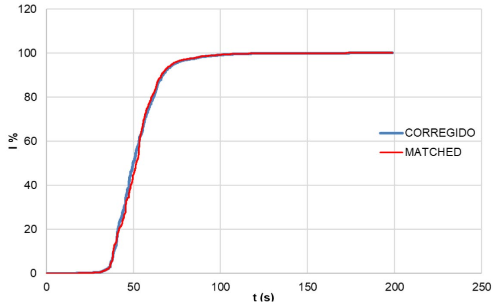

Figure 6. Intensity of arias corrected (unadjusted) and spectrally adjusted.

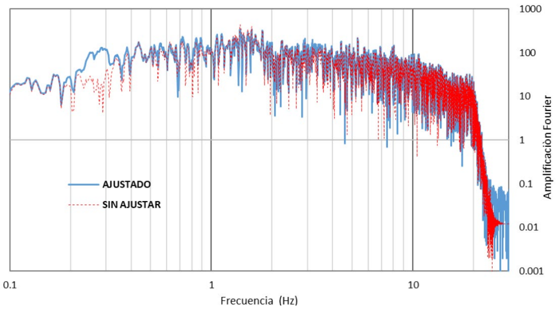

Figure 7. Intensity of arias of the corrected (unadjusted) and spectrally adjusted record. (Fourier spectrum)

### 2.2.2 Site characterization

Three (3) test pits were made on the surface of the laid slope (C-1; C-2 and C-3). Additionally, one (1) test pit was made on the lateral slope (C-4). Table 1 lists the designation of the test pits and their location. Figure 1 shows the general view of the location of the investigations carried out (test pits).

Table 2: Pit and Location.

| Pit | Location |
|---|---|
| C-1 | Top of slope |
| C-2 | Central part of the slope |
| C-3 | Lower part of the slope |
| C-4 | Lateral part of slope |

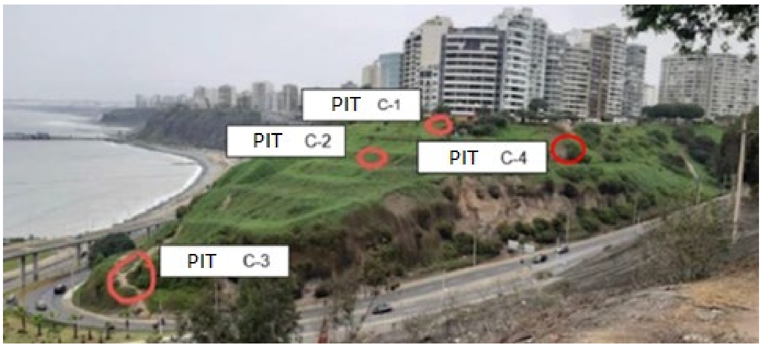

Figure 8. General view of the location of the investigations carried out (pit), July 2020.

### 2.2.3 Geotechnical properties of materials

Based on the results of laboratory tests corresponding to the large-scale direct shear tests carried out both at the Geotechnical Laboratory of the Peruvian-Japanese Research Center (CISMID) of the National University of Engineering (UNI) and by MarJent, the strength parameters of the extracted samples were estimated.

Figure 9.- In situ large-scale direct shear test, conducted by MarJent (October, 2020).

Figure 10.- In situ large-scale direct shear test, conducted by CISMID-UNI (September, 2020).

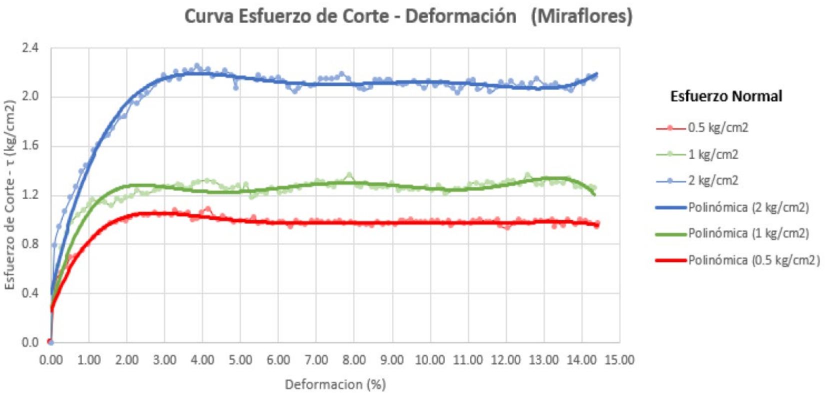

Figure 11.- Shear Stress - Deformation Curve

The following is the list of strength parameters obtained from large-scale direct shear tests.

Table 3: Strength parameters of materials obtained from the large-scale shear test, CISMID-UNI (September, 2020) and MarJent (October, 2020).

| Probing / Sample | Maximum stresses | | Failure stresses | | SUCS (*) |
|---|---|---|---|---|---|
| | c (kg/cm2) | φ (°) | c (kg/cm2) | φ (°) | |
| C-1 | 0.45 | 38 | 0.1 | 39.5 | GW |
| C-2 | 0 | 41 | - | - | GM |
| C-3 | 0.25 | 37.5 | 0.15 | 37 | GW-GM |
| C-4 | 0.59 | 39.7 | 0.44 | 38.7 | GW |

Note: (*) Granulometric analysis carried out to material of diameter minus 3”.

In order to estimate the variation of the particle sizes that make up the conglomerate, an integral particle size analysis was performed. Figure 12 presents the integral granulometric curve of the materials obtained.

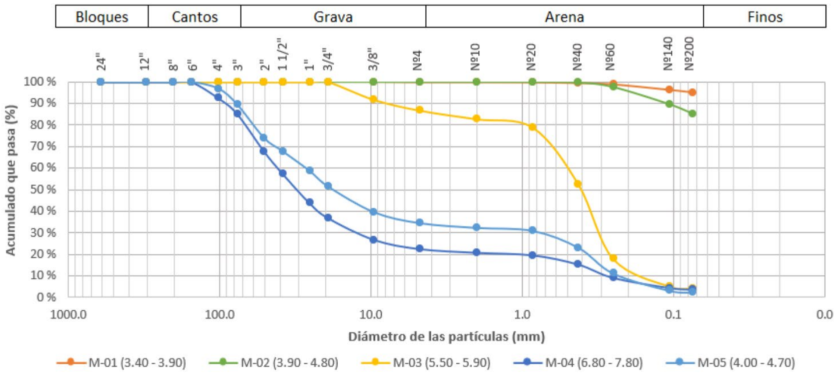

Figure 12.- Granulometric curve integral

### 2.2.4 Calibration of materials

To perform the numerical analysis it is necessary to make the correct representation of the geotechnical material by means of a constitutive model, in this research the Hardening Soil constitutive model was chosen, where in order to have more realistic values, a simulation of the large-scale direct cut was performed in the Plaxis 3D software.

The following is the result of the calibration of the slope material, the Lima conglomerate, from large-scale direct shear results adjusted to the Hardening Soil constitutive model.

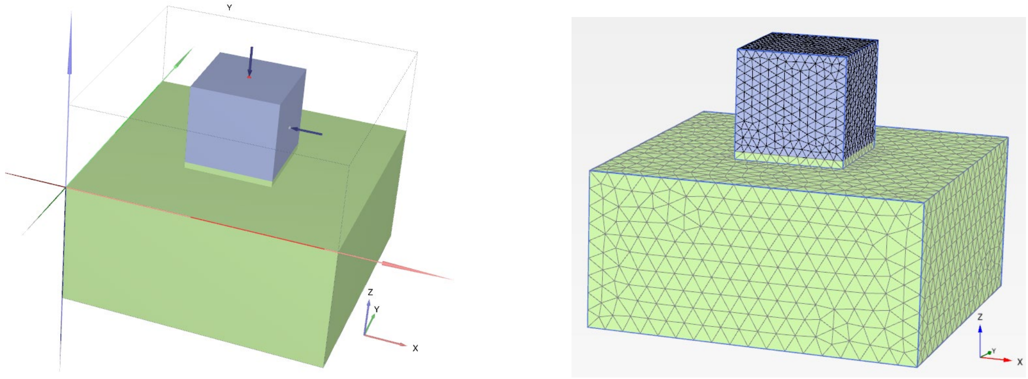

Figure 13.- Large Scale Direct Cutting Simulation

Table 4: Parameters of the Hardening Soil constitutive model. Miraflores Sector.

| Output parameters MIRAFLORES SIDE | | | |
|---|---|---|---|
| c (kPa) | 43 | | |
| Ø (°) | 39 | | |
| Stresses σ3 (kPa) | 49 | 98 | 196 |
| Young's modulus E50 (kPa) | 53980 | 72105 | 105231 |
| Eoed (kPa) | 35986 | 48070 | 70154 |
| Eur (kPa) | 161939 | 216314 | 315692 |
| Poisson | 0.2 | 0.2 | 0.2 |
| Ko ratio according to Jacky | 0.3748 | | |
| reduction coefficient "Rf" | 1.2147 | | |
| Exponential dependence of stiffness "m" | 0.4815 | | |

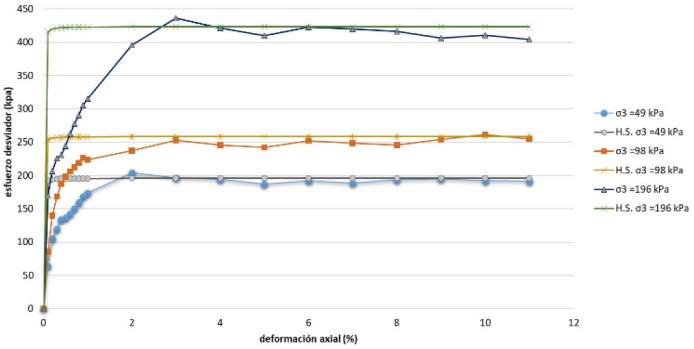

Figure 15.- Fitting the data to the Hardening Soil constitutive model. (Deviator effort vs. Axial deformation)

# 3 Results

## 3.1 Modification of surface seismic response

Dynamic amplification at the surface is shown:

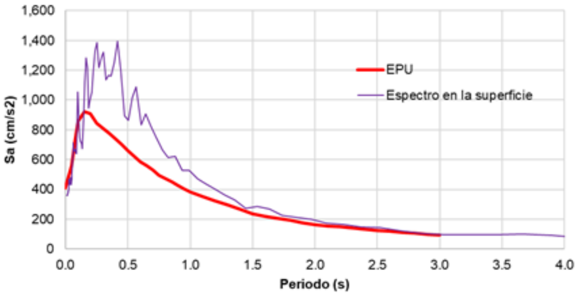

Figure 14.- Response spectrum resulting from the one-dimensional nonlinear response analysis on the slope surface.

## 3.2 Three-dimensional numerical simulation of static performance

Initially, a three-dimensional static analysis was performed in order to evaluate the deformations caused by the buildings, and the stability was evaluated according to the parameter reduction method.

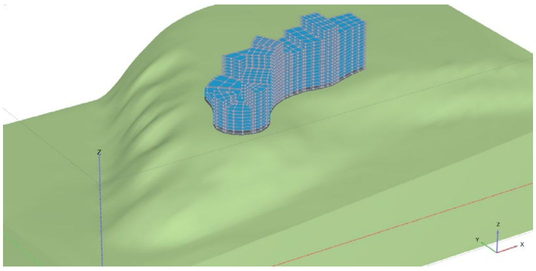

Figure 15. Slope and Building Simulation

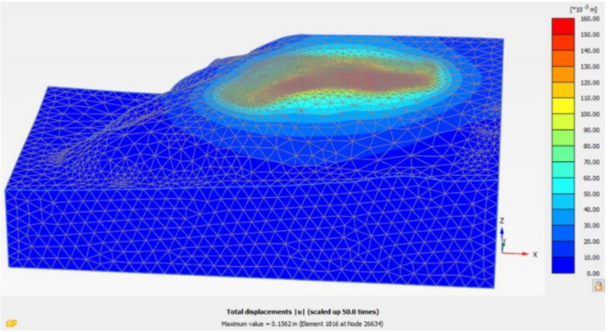

Figure 16. Deformations due to building loads

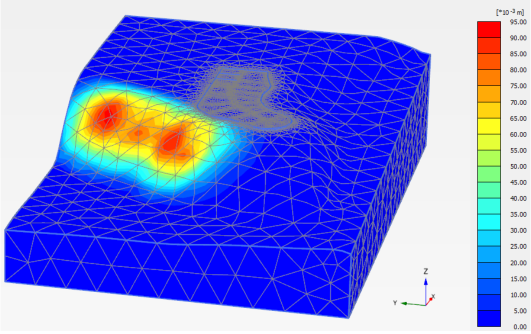

Figure 17. Fault surface, by static analysis

### 3.3 Three-dimensional numerical simulation of dynamic behavior

As can be seen in the previous section, Figure 18 shows a plan view of the study area, Costa Verde Bajada de Armendariz - Armendariz Sector.

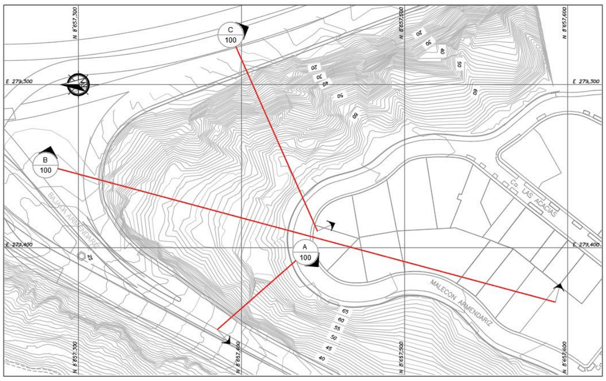

Figure 18. Analysis sections in the Miraflores area

From section 2.3.2. we observe that Section C contains the failure zone of the static analysis, which is why for the subsequent three-dimensional analysis, we will work with a three-dimensional section with a thickness of 50 meters, as shown in the following figure.

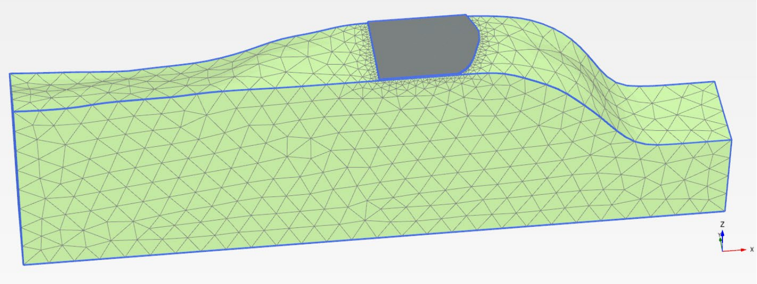

Figure 19. Analysis Section, for dynamic simulation

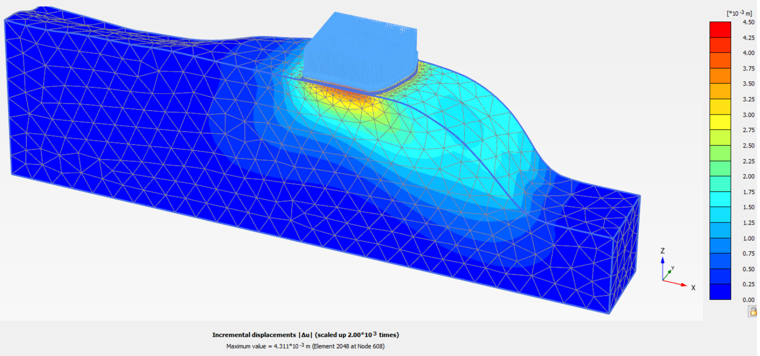

Figure 20. Due to the load of the buildings

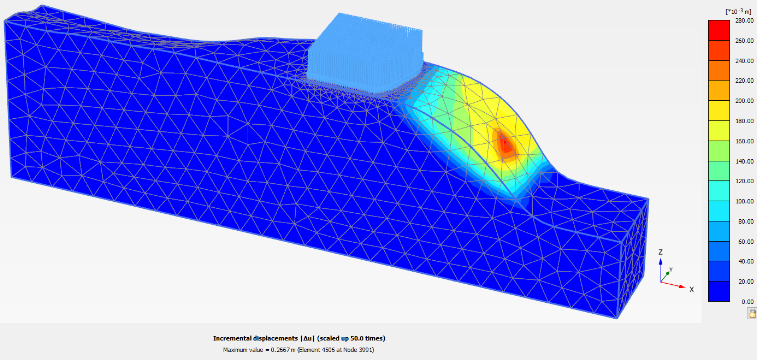

Figure 21. Static Safety Factor

The results of the dynamic numerical simulations of the analysis section in a frontal view are shown below.

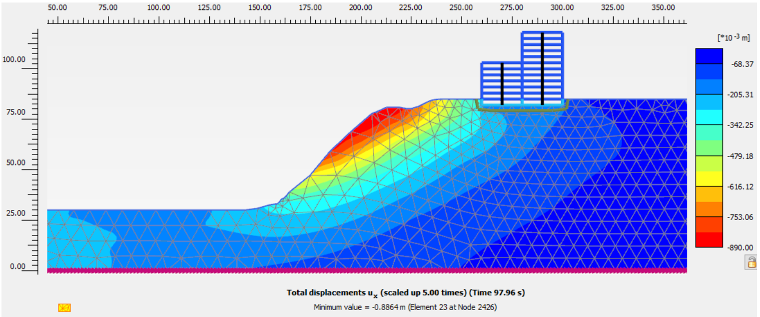

Figure 22. Horizontal displacements from dynamic analysis in Section C. $UU_{xx}$ = -0.89 m.

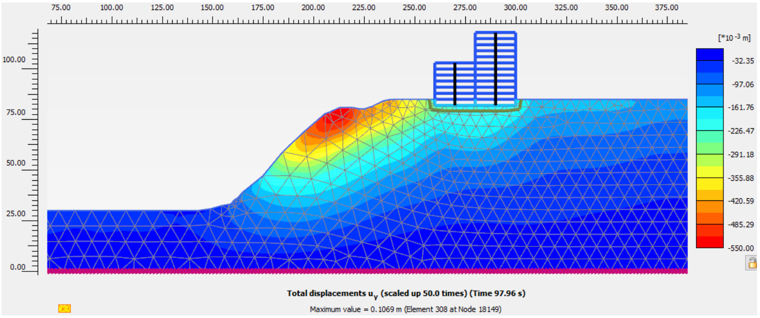

Figure 23. Vertical displacements from the dynamic analysis in Section C. $UU_{yy}$ = 0.11 m.

## 4 Conclusions

The strength parameters of the conglomerate were estimated by means of large-scale shear tests, in this way the parameters were estimated in a more realistic way since the particles are evaluated in their real size.

The seismic response of the ground is a complex process that involves a large number of variables, ranging from the type of soil and its nonlinear behavior, stiffness of the slope material, soil-structure interaction phenomena, among others.

The application of numerical techniques in a three-dimensional analysis shows a more realistic perspective of the study project to analyze the most vulnerable areas.

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