Seismic response of slopes
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ABSTRACT The stability of foundations in mountainous regions is a significant issue with respect to earthquake hazards. Not only structures supported by these foundations can be affected, but also entire networks of roads, railways or other lifelines can be interrupted, causing partial or even total network failure. The quantification of the factors affecting the stability of a foundation located on a slope is an important step in understanding the underlying processes as well as determining the risk posed to such foundations. A detailed analysis of the influence of slopes on foundation during seismic event is very important for the assessment of the performance of the structure, considering the recent urban spread of buildings and infrastructure in seismically active regions with steep topography. The practical application of this analysis will provide necessary basic knowledge for risk assessment of the infrastructure lying in steep terrain and will influence future design codes in terms of the performance based design.

1 INTRODUCTION

The soil-structure interaction determines the behaviour of a structure during an earthquake event. Frequently, only a single component, either the soil or the structure, is considered in seismic analysis, while the other is replaced by a simple system. However, the behaviours of the both systems are reciprocally dependent. Usually the simplifications used to replace the soil system are insufficient for a lot of cases (e.g. Kuhn et al. 2008), even though, for some cases, particularly when the structure is reasonably light and the soil is comparably stiff, the assumptions are valid.

A complete analysis of the soil structure interaction, taking into account the real soil behaviour has not been considered very often in the past, with the exception of extraordinary high-risk structures (e.g. Pecker 2003 and 2004). Advanced physical and numerical modelling has been carried out to justify and verify extraordinary design procedures for those structures. Nevertheless, more extensive analyses of the soil structure interaction should also be carried out for standard structures in the future, especially if failure of these structures affects entire networks. For example, the failure of a bridge foundation and therefore of the entire bridge might lead to much larger consequences than the collapse of a single building. An additional component, which usually is not considered in the design, is that the response of the foundation-soil system influences the seismic performance of the superstructure significantly (Gazetas et al. 2003 and 2004).

In earthquake engineering, the structural response is investigated through static and dynamic approaches (Chopra 1995). Dynamic investigations represent the reality most accurately, but they are both very expensive and time consuming and thus more complex than the pseudo-dynamic (static) ones. Pseudo-dynamic approaches (Bachmann 1992 and Dazio et al. 2009) present a significantly faster design alternative even though some phenomena cannot be considered as these methods are either based on a load or on static physical or numerical experiments. In this study the author will focus only on the results obtained from a dynamic analysis.

Reports from recent earthquakes showed that the foundation is one of the most vulnerable components of a structure (e.g. Mendoza et al. 1988). This foundation failure occurs in levelled ground as well as in slopes. Although some research regarding non-linear response of the soil-foundation systems has been conducted (Wolf 1987, Gazetas and Mylonakis 1998), these studies focus on actively loaded founda-
tion (e.g. Wolf 1987) or on foundations on flat surfaces (e.g. Gazetas and Mylonaki 1998). A transfer to more complex topographic conditions has not been conducted yet, even though this represents a necessary condition for the safety of lifelines. Typical examples of civil engineering structures on slopes are bridge foundations or electrical power towers. Many lifeline structures are located in seismically active, mountainous areas, and, as a result, their foundations are located on steep slopes. The structural stability of these foundations must be guaranteed especially for post-earthquake disaster management.

Recently, a screening method for the safety of lifelines in slopes is being developed at the Institute for Geotechnical Engineering at ETH Zurich, taking into account the slope itself and incorporating the effect of the behaviour of the slope on lifelines above or below it (Laue 2014).

In this study the author will analyse how the terrain inclination influences the output signal on the ground surface during a seismic event. To accomplish this goal, a spectral amplification analysis was conducted by comparing the input acceleration (bedrock) and the output signal (surface).

The results of this study aim to improve and develop better design methods for structures, in seismically active, mountainous areas. This is especially applicable in emerging economies, where growing populations are driving the need for expanded infrastructure both within cities and between them. Further, the results may be applied to assess the seismic performance of many existing structures.

2 METHODS

The general purpose of the project is to understand the topographic effect on the response signal at the surface during earthquakes and to develop improved analysis and design methods. To be able to achieve these goals, physical experiments and numerical simulations will be used to assess scientific, social and economic impact. The research question will be approached in two ways:

- Physical modelling
- Numerical modelling

The physical modelling tests were conducted with the dynamic centrifuge at the University of California San Diego (UCSD). Numerical modelling experiments were carried out with the finite element model program PLAXIS (Brinkgreve, 2010) to verify the obtained results. In this study the author will only present the results obtained from the physical experiments.

2.1 Physical modelling

All the physical modelling experiments were carried out at 60 x g with the 2-meter radius beam centrifuge at the UCSD (Figure 1).

Figure 1. Centrifuge UCSD.

The centrifuge can reach a maximum g-level of 130 or 50 g-tons (payload times g-level) respectively.

Centrifuge modelling allows simulating big scale geotechnical problems in a reduced model. The model is spun at a certain g-level until the stress levels in the small model reach the ones of the prototype.

The dynamic excitation is reproduced with a high performance servo-hydraulic centrifuge shaker. The nominal shaking force is 21 kN and the maximum table displacements is ±0.635 cm in model scale. The shaker is capable to operate under different g-levels and covers frequencies up to 200Hz.

Dynamic tests with the centrifuge have shown in the past that the shaker is a reliable tool for generating ground acceleration, excess pore water pressure and soil structure deformation at stress level equal to the prototype scale.

The scaling laws for centrifuge testing have been derived by (Schofield 1980) and are shown in Table 1. The soil used for the experiments is dry sand and
therefore no problem exists related to the modelling of the viscosity of groundwater.

Table 1. Scaling law for centrifuge testing.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model/prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>$1/N$</td>
</tr>
<tr>
<td>Acceleration</td>
<td>$N$</td>
</tr>
<tr>
<td>Velocity</td>
<td>$1$</td>
</tr>
<tr>
<td>Strain</td>
<td>$1$</td>
</tr>
<tr>
<td>Force</td>
<td>$1/N^2$</td>
</tr>
<tr>
<td>Mass</td>
<td>$1/N^3$</td>
</tr>
<tr>
<td>Time</td>
<td>$1/N$</td>
</tr>
</tbody>
</table>

The major advantage of the servo hydraulic shaker over the mechanical earthquake actuators is that the servo-hydraulic systems are capable to reproduce real life earthquake motions instead of motion with just predefined fixed amplitude and frequencies.

2.2 Soil

A non-standardized geotechnical soil (the so called “Coronado Sand”) was used in the series of physical modelling tests. Since performed tests took place in a very early stage of the research, only few information regarding the soil parameter and its properties were available. Some of the basic properties of the Coronado sand are summarized in Table 2. The shear wave velocity $V_s$ and the shear modulus $G$ were assumed based on the literature research on sand parameters (Seed et al. 1970 and Studer et al. 2007). The preparation method for the samples was the air pluviation.

Table 2. Properties of the Coronado Sand.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>USCS Classification</td>
<td>SP</td>
<td>-</td>
</tr>
<tr>
<td>Density $\rho$</td>
<td>1800...2000 kg/m$^3$</td>
<td></td>
</tr>
<tr>
<td>Friction angle $\varphi'$</td>
<td>30 $^\circ$</td>
<td></td>
</tr>
<tr>
<td>Cohesion $c'$</td>
<td>0</td>
<td>N/mm$^2$</td>
</tr>
<tr>
<td>Water content $w$</td>
<td>1</td>
<td>%</td>
</tr>
<tr>
<td>Shear wave velocity $V_s$</td>
<td>200 - 300 m/s</td>
<td></td>
</tr>
<tr>
<td>Shear modulus $G$</td>
<td>50 - 70 N/mm$^2$</td>
<td></td>
</tr>
</tbody>
</table>

2.3 Input motion

In all experiments the input displacement was of sinusoidal type with variable maximal amplitude ($25 – 45$ mm) and frequency (1 – 2.5 Hz). The duration of the seismic excitation was between 90 and 120 seconds and the input signal was varied using a Hanning window (Testa et al., 2004). The input motion used for the physical experiment is shown in Figure 2 (prototype scale).

2.4 Measurement instrumentation

The instrumentation in these experiments consisted of accelerometers and LVDTs. The piezoelectric accelerometers are 352M54 produced by PCB Piezotronics. They measure 1D (single axis) accelerations of up to $\pm$100 g in their own orientation at a rate up to 13 kHz. Each accelerometer is about 0.6 cm in diameter and 2.5 cm long.

An LVDT was connected to the shaking table and it was used to measure the displacement induced by the shaker over the time. The LVDT has a stroke length of $\pm$1.27 mm at model scale.

2.5 Test setup

Three types of experiments were conducted:

1) The first set of experiments was conducted with a levelled soil layer of a constant thickness $H = 6.3$ m. These experiments were conducted with the purpose of estimating the natural frequency of the soil layer during a seismic excitation.

2) The second part of the experiments aimed to analyse the influence of a 20-degree slope on the output signal amplification at the surface.

3) In the last sets of experiments a perpendicular input motion perturbed the same slope with an inclination of 20-degree. The goal of the experiment was to analyse the effect of...
the shaking direction on the output response signal at the surface.

Figure 3 shows the tests setup and the position of the instrumentations.

Figure 3. Experiments overview. 1) First set of experiment. 2) Second set of experiments. 3(a) Side view 3rd set of experiment. 3(b) Top view 3rd set of experiment.

The water level was considered to be located under the bedrock and therefore was not relevant for the analysis.

Since the slope inclination angle was smaller than the internal friction angle, the stability of the slope in the static and dynamic experiments was guaranteed.

A rigid box was used for all tests, having the internal dimension L x B x H = 356mm x 356mm x 241mm. The walls of the box are rigid and the influence of the boundary effects are acknowledged and accepted in this early stage of the research.

3 RESULTS AND DISCUSSION

In this section the results obtained from the physical modelling experiments are presented.

3.1 Natural frequency of a horizontal soil layer

The first natural frequency of a soil layer with the thickness H can be approximately calculated using (1), where $V_s$ is the shear wave velocity:

$$f = \frac{V_s}{4H} \quad (1)$$

Since the shear wave velocity of the Coronado sand was unknown, the natural frequency of the soil layer was approximated experimentally through physical modelling tests. To reach this, two accelerometers were installed in the middle of the box. One was fixed at the bottom of the box (bedrock) and the other one was placed underneath the surface of the soil layer. The thickness $H=6.3$m of the soil layer and the soil density $\rho=1900$ kg/m$^3$ were kept constant throughout the experiments. The input motion’s frequency and amplitude were varied. All the experiments were conducted at 60g.

The Fast Fourier Transformation (FFT) of the input (bedrock) and output (surface) acceleration were calculated and the spectral ratio between the surface and bedrock signal ($\text{FFT}_{\text{Surface}}/\text{FFT}_{\text{Bedrock}}$) was determined. 13 tests were conducted in total and the resulting spectral amplification is shown in Figure 4.

Figure 4. Natural frequencies of the horizontal soil layer with thickness $H = 6.3$ m

As shown in Figure 4 it is clear that the main natural frequency of the soil layer with the thickness $H=6.3$m is around 12Hz. Using the relation (1) it was possible to back calculate the shear wave velocity $V_s\approx300$ m/s. According to Motezadian et al. 2011, this value corresponds to a stiff soil with a standard penetration resistance $N_{60} = 15 – 60$. These values are also in a good agreement with the ones assumed previously in Chapter 2.2 for the Coronado Sand (Studer et al. 2007).

3.2 Topographic effect

Similar experiments were conducted to verify the topographic effects on the spectral amplification of a soil layer with a surface inclination of 20 degrees. The positions of the sensors were the same like in the previous experiments. One accelerometer was placed at the bottom of the box and the other one underneath the surface in the middle of the slope. In Figure 5 is
shown the geometrical setup and the position of the accelerometers. A total of 6 experiments were conducted. The geometry and the soil density $\rho$ were kept constant. The amplitude and the frequency of the input signal were varied. The results of the spectral ratio for this set of experiments are shown in Figure 5.

![Figure 5](image)

**Figure 5.** Natural frequencies of the soil model with surface inclination. Shaking in the slope direction.

As shown in Figure 5 the maximal spectral amplification occurs at the first natural frequency of the soil model at 8 Hz. This value is significantly lower compared with the natural frequency of the soil layer without a surface inclination. This means that a higher frequency input signal will cause a higher amplification of the motion in the situation of a horizontal surface of the soil than, when compared with the inclined surface, which is more susceptible to low frequency earthquake signals.

Another interesting feature is the wide range of frequencies where the amplification reaches the highest values ($2 - 2.5$) and the lack of a clear singular peak.

### 3.3 Influence of the shaking direction

Another series of experiments were conducted with the purpose of analysing the effect of the shaking direction on the natural frequency of an inclined soil layer. In these series of experiments the shaking direction was perpendicular to the slope direction. The geometrical setup of the slope, the location of the instrumentations and the density of the soil were the same as in the previous experiments. The amplitude and frequency of the input acceleration were varied. The average amplitude was 20% larger than the previous experiments. The accelerometers are oriented in the same direction of the input motion. Figure 6 shows the spectral amplification near the surface in the middle of the slope.

![Figure 6](image)

**Figure 6.** Natural frequencies of the soil model with surface inclination. Shaking perpendicular to the slope direction.

The first and the second natural frequencies ($f_1$ and $f_2$) are 8 and 12 Hz. These values correspond to the natural frequencies of the inclined and flat models showed previously. Not only the frequencies are the same but also the amplification values are similar.

Since the shaking direction is perpendicular to the slope and no topographic changes are present in the shaking direction, it is reasonable to think that one of the natural frequencies is similar to the one obtained for the flat model.

A detailed analysis of the experiment showed that at the beginning of the shaking for the first loading cycles, only one peak was present at $f = 12$ Hz. At this moment the waves generated by the shaker are still propagating perpendicular to the slope direction. After a while these waves start to be reflected by the rigid walls of the box and the reflected waves start to propagate in the direction parallel to the slope. From this moment on, simultaneously, another new resonant frequency ($f = 8$ Hz in Figure 6) starts to become visible. This value is similar to the one observed in the inclined model subjected to a shaking parallel to the slope direction. This phenomenon of wave reflection is more obvious in this last series of experiments because the average the amplitude of the input acceleration was 20% larger than the previous ones.

Furthermore the results revealed that if the shaking is perpendicular to the slope direction, the range of resonant frequencies is larger when compared to the previous cases. Actually not only low frequency earthquakes are dangerous but also high frequency signals as well.
SUMMARY AND CONCLUSIONS

The experimental results revealed that the soil parameters assumed for the Coronado Sand are consistent with the information gained from the literature research. These parameters are a reliable base for starting a numerical analysis with simple constitutive models such as Mohr Coulomb, integrated in PLAXIS. Further on more sophisticated experiments are needed for more complex constitutive models.

The spectral amplification analysis of the inclined soil layer showed that a low frequency earthquake could be more destructive a high frequency one.

The direction of input motion showed to have an influence on the signal amplification. If the slope is subjected to shaking perpendicular to its direction the signal amplification is the result of the superposition of the amplifications obtained from the horizontal and the inclined systems subjected to parallel shaking.

The results obtained from the centrifuge experiments using the dynamic the shaker represent a good starting point for the implementation of more complex physical models aiming to investigate the soil structure interaction during seismic events.

REFERENCES


