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Building dams on rock or soft soil – frequency-domain analysis of dynamic dam-foundation interaction

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SYNOPSIS   This paper is concerned with the future design of new and the assessment of existing earth dams. It aims to understand what the effect of a soft soil foundation for earth dams is. The effects of a compliant foundation are more pronounced under dynamic events such as earthquakes. This study uses dynamic finite element analysis to investigate the dynamic response of earth dams during earthquakes. It is shown that the presence of a soft foundation layer increases the fundamental period of vibration of the dams and depending on the properties of the dam and foundation it may lead to amplification or de-amplification of the seismic accelerations. This is an important observation as design codes (e.g. EC8) need to consider the frequency content of the earthquake and the natural frequencies of the dam structure. Therefore, this study may lead to a better seismic design of earth dams.

1. INTRODUCTION

Earth dams are massive structures built in river valleys to hold water and create large reservoirs. They are usually constructed on some soft alluvial sediment found at the riverbed. The presence of such sediment affects the dynamic and seismic response of earth dams.

It is known that a soft foundation layer affect the dynamic vibrations of dams leading to changes in the amplification of accelerations and the natural periods of vibration (Gazetas, 1987). This is known as dynamic dam-foundation interaction (DFI) which is a subset of the well-known phenomenon of soil-structure interaction (SSI) (Wolf, 1985) which is indeed an issue for many structures and civil infrastructure.

This paper presents a computational study related to DFI. In particular, the effects of DFI on the natural modes of vibration of earth dams are investigated using modal dynamic finite element analysis. It is shown that a

dam built on soft soil exhibits a softer response than a dam build on rigid rock.

2. DYNAMIC RESPONSE OF EARTH DAMS

To take account of DFI effects, a plethora of relevant studies has been conducted, using both small-scale physical modelling (Saleh & Madabhushi, 2010) and advanced numerical simulations (Bilici, et al., 2009; Shire et al., 2013; Pelecanos et al., 2012b), using finite elements (FE) (Kontoe et al., 2013; Pelecanos et al., 2015; 2018b; 2019a), boundary elements (BE) (Abouseeda & Dakoulas, 1996), infinite elements (Zhao & Valliappan, 1993), the scaled-boundary element method (Wolf, 2003) etc. In general, dam-reservoir interaction effects are considered insignificant for earth dams (Pelecanos et al., 2013a, 2016, 2017).

The issue of DFI is not new and has been studied widely since the early days of earthquake engineering. The early work of Chopra & Perumalswami (1971) showed that the response of a dam founded on an elastic foundation is damped (i.e. exhibits smaller values of acceleration amplification) due to DFI effects. Later, Idriss et al. (1974) concluded that DFI is strongly affected by the natural periods and material properties of both the dam and foundation. A subsequent study by Abdel-Ghaffar & Scott (1981) showed that energy is dissipated through wave radiation in the dam foundation during the transient shaking of the dams. Moreover, Dakoulas (1993a,b) and his colleagues (Dakoulas & Hsu, 1993, 1995) extended the work for three-dimensional (3D) dam geometries, examining the influence of elastic dam canyons and suggested that the dam response is affected by the impedance between the dam and the canyon.

Of particular importance is the seminal work of Dakoulas & Gazetas (1987) who were able to quantify the effects of DFI on the dynamic response of earth dams. They considered idealised geometries of triangular earth dams resting on uniform foundation layers and used the shear beam method (Ambraseys, 1960; Dakoulas & Gazetas, 1985). They showed that the fundamental period of vibration of a dam is increasing with increasing foundation thickness and dam crest length. They developed relevant simplified design charts that can be used to estimate reliably the "effective" fundamental period of vibration of earth dams founded on soft foundation deposits. However, all the afore-mentioned studies were conducted using the shear beam method (Ambraseys, 1960) which was found to yield different results to the more accurate FE method (Lo & Pelecanos, 2018).

Since the effects of DFI are recognised, the vast majority of recent studies related to the seismic response of earth dams resting on soft foundations considered in a monolithic way the modelling of the dam and its

foundation using transient dynamic analysis (Elia et al., 2011; Pelecanos et al., 2012a; 2013b; 2015; 2018a; 2019b; Han et al., 2016). Not many studies considered the case of "de-coupled" dam and foundation domains (Burman et al., 2012).

3. CASE STUDY: LA VILLITA DAM, MEXICO

La Villita is a 60m high zoned earth dam in Mexico with a crest about 420m long, founded on a 70m thick alluvium layer. The dam cross-section is composed of a central clay core of very low permeability, with sand filters and rockfill shells. The cross-sectional geometry of the dam is shown in Figure 1.
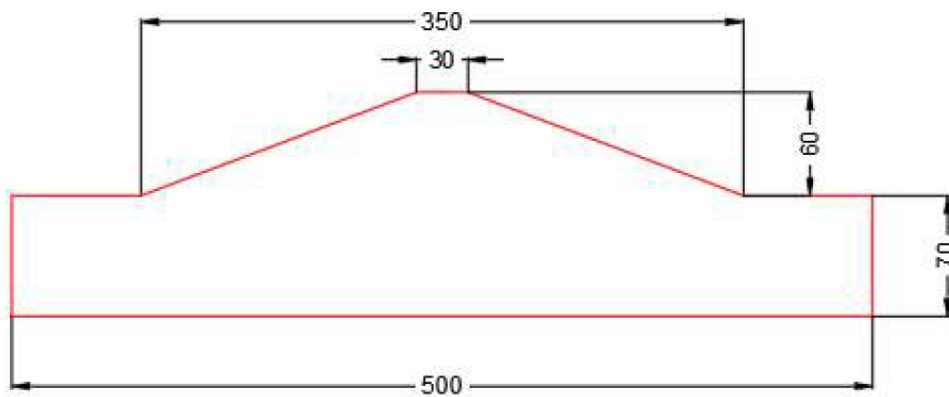

Figure 1. Geometry of La Villita dam

Available deformation and strength material properties of La Villita dam are listed in Table 1 (Elgamal, 1992). As far as dynamic response is concerned, deformation properties are of interest and govern the natural periods and modes of vibration of the dam. More information about the material properties may be found by Pelecanos (2013) and Pelecanos et al. (2015).

Table 1. Material properties of La Villita dam

No	Part	Unit weight, ρ [kg/m^3]	Shear Modulus, G [MPa]	Cohesion, c [kPa]	Angle of shearing, ϕ [deg]
1	Dam core	2000	200	5	25
2	Dam shells	2080	200	5	45
3	Foundation alluvium	2080	200	5	35

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Using the commercial FE package ANSYS, the La Villita dam was discretised into a FE mesh, as shown in Figure 2. Linear elastic material properties were assigned to the dam materials according to Table 1.
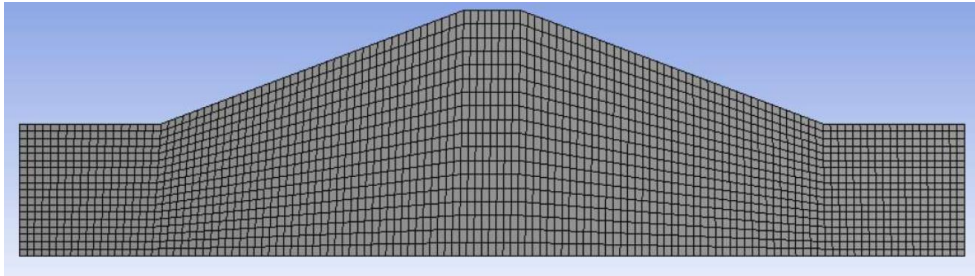
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Figure 2. Finite element mesh of the dam

Subsequently, the effects of the foundation layer on the dynamic response of the dam are assessed. More specifically, the dynamic characteristics of the foundation layer are modified and different cases are considered. It is known from site response analysis that the fundamental period of vibration of a uniform homogeneous soil layer is (Kramer, 1996):

$$T_1 = \frac{4 \cdot H}{V_s} \qquad (1)$$

Where, H is the height of the soil layer and V_s is the shear wave velocity of the foundation soil. The latter quantity, V_s, is dependent on the shear modulus, G, of the material, according to:

$$V_s = \sqrt{\frac{G}{\rho}} \qquad (2)$$

Where, G is the shear modulus and ρ is the mass density of the soil material. In this section, the influence of both the foundation thickness, H, and stiffness, G, on the dynamic response of the dam are assessed. Here, only the FE method is used as there are limited relevant closed form solutions based on the SB method.

3.1. Foundation stiffness

For the first case, the foundation stiffness (shear modulus, G) is assessed. The analyses are run for different values of G. The following three scenarios are considered: $G = 160, 200, 240 \ MPa$.

The dam mesh shown in Figure 2 is used for the FE analysis and again modal dynamic analysis in the frequency domain is performed. The obtained values of the first 5 natural frequencies are listed in Table 2 and shown graphically in Figure 3.

Table 2. Natural frequencies of vibration for various values of foundation stiffness

Shear Modulus, G	Natural Frequency [Hz]				
[MPa]	1st mode	2nd mode	3rd mode	4th mode	5th mode
160	0.726	1.027	1.183	1.265	1.458
200	0.794	1.132	1.299	1.371	1.595
240	0.859	1.225	1.402	1.468	1.719

Considering the obtained values for the natural frequencies of vibration one may observe that higher modes are associated with larger values of frequency, i.e. smaller values of natural period, T_n. This was expected, as higher modes are stiffer, and this is known from basic structural dynamics (Chopra, 1995).
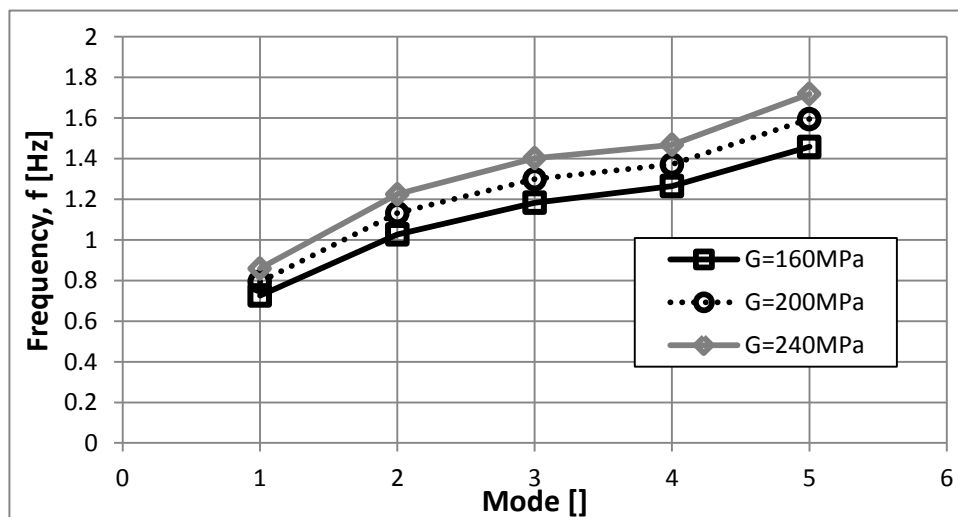

Figure 3. Natural modal frequencies of vibration for various values of foundation stiffness

Moreover, it may be observed that higher values of G show consistently larger values of frequency (again, smaller T_n), therefore exhibiting a stiffer dynamic response. This was again expected, as higher values of G lead to

larger values of V_s (according to Equation 2) and therefore smaller values of T_n (according to Equation 1).

3.2. Foundation thickness

For the second case, the foundation thickness, H, is assessed. The analyses are run for different values of H. The following three scenarios are considered: $H = 0, 40, 70\ m$. The dam mesh shown in Figure 2 is again used for the FE analysis and again modal dynamic analysis in the frequency domain is performed. The obtained values of the first 5 natural frequencies are listed in Table 3 and shown graphically in Figure 4.

Table 3. Natural frequencies of vibration for various values of foundation thickness

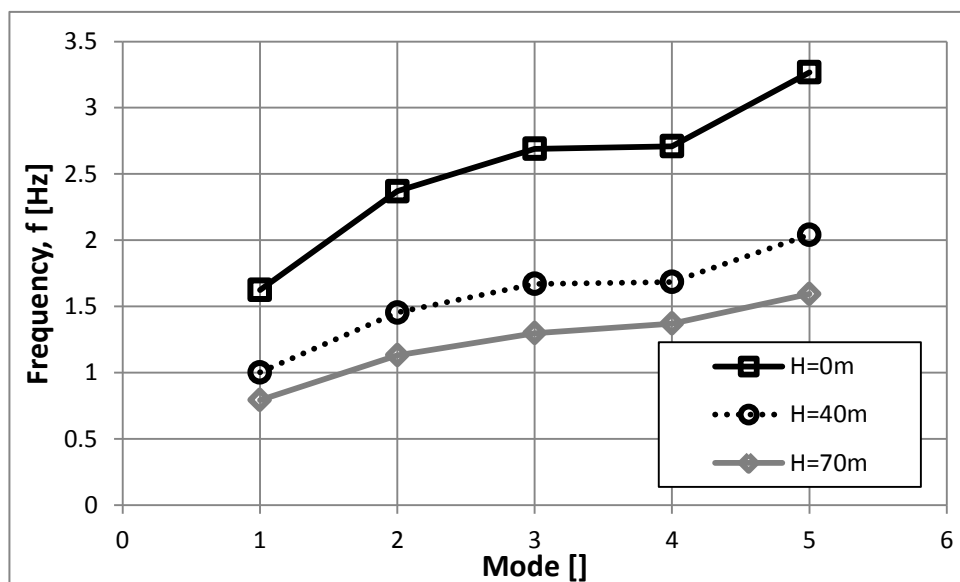| Foundation depth, H	Natural Frequency [Hz]				
[m]	1st mode	2nd mode	3rd mode	4th mode	5th mode
0	1.625	2.370	2.690	2.709	3.267
40	1.003	1.454	1.670	1.685	2.042
70	0.794	1.132	1.299	1.371	1.595

Figure 4. Natural modal frequencies of vibration for various values of foundation thickness

Considering the obtained values for the natural frequencies of vibration one may observe that higher modes are associated with larger values of frequency, i.e. smaller values of natural period, T_n. This was again expected, as higher modes are stiffer, and this is known from basic structural dynamics (Chopra, 1995).

Moreover, it may be observed that higher values of H show consistently smaller values of frequency (here, larger T_n), therefore exhibiting a softer dynamic response. This was again expected, as higher values of H lead to larger values of T_n (according to Equation 6).

4. CONCLUSIONS

This paper presents a computational study to assess the influence of a soft foundation on the dynamic behaviour of earth dams. This is related to the dynamic response of such dams under strong earthquake loading. The findings of this study may be summarised as follows:

- Stiffer foundations (i.e. larger values of shear modulus, G) lead to larger values of natural frequencies and therefore a softer dynamic dam response.
- Thicker foundation layers lead to smaller values of natural frequencies and therefore a stiffer dynamic dam response.

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REFERENCES

Abdel-Ghaffar, A.M. and Scott, R.F., 1981. Vibration tests of full-scale earth dam. Journal of the Geotechnical Engineering Division, 107(3), pp.241-269.

Abouseeda, H. and Dakoulas, P., 1996. Response of earth dams to P and SV waves using coupled FE-BE formulation. Earthquake engineering & structural dynamics, 25(11), pp.1177-1194.

Ambraseys, N., 1960. On the shear response of a two-dimensional truncated wedge subjected to an arbitrary disturbance. Bulletin of the seismological society of America, 50(1), pp.45-56.

Smart Dams and Reservoirs

Bilici, Y. et al., 2009. Stochastic dynamic response of dam reservoir foundation systems to spatially varying earthquake ground motions. Soil Dynamics and Earthquake Engineering, Volume 29, pp. 444-458.

Burman, A., Nayak, P., Agrawal, P. & Maity, D., 2012. Coupled gravity dam-foundation analysis using a simplified direct method of soil-structure interaction. Soil Dynamics and Earthquake Engineering, Volume 34, pp. 62-68.

Chopra, A. & Perumalswami, P., 1971. Dynamics of earth dams with foundation interactions. Journal of the Engineering Mechanics Division, ASCE, 97(1), pp. 181-191.

Chopra Anil, K., 1995. Dynamics of structures. Theory and Application to Earthquake Engineering. Prentice Hall, New Jersey.

Dakoulas, P., 1993a. Earth dam-canyon interaction effects for obliquely incident SH waves. Journal of Geotechnical Engineering, 119(11), pp.1696-1716.

Dakoulas, P., 1993b. Response of earth dams in semicylindrical canyons to oblique SH waves. Journal of engineering mechanics, 119(1), pp.74-90.

Dakoulas, P. and Hsu, C., 1993. Lateral response of dams in semi-elliptical rigid canyons. Soil Dynamics and Earthquake Engineering, 12(8), pp.497-507.

Dakoulas, P. and Hsu, C.H., 1995. Response of dams in semielliptical canyons to oblique SH waves. Journal of Engineering mechanics, 121(3), pp.379-391.

Dakoulas, P. & Gazetas, G., 1985. A class of inhomogeneous shear models for seismic response of dams and embankments. Soil Dynamics and Earthquake Engineering, 4(4), pp. 166-182.

Dakoulas, P. & Gazetas, G., 1987. Vibration characteristics of dams in narrow canyons. J. Geot. Engrg., ASCE, 113(8), pp. 899-904.

Elgamal, A.W., 1992. Three-dimensional seismic analysis of La Villita dam. Journal of geotechnical engineering, 118(12), pp.1937-1958.

Elia, G., Amorosi, A., Chan, A.H.C. and Kavvadas, M.J., 2011. Fully coupled dynamic analysis of an earth dam. Geotechnique, 61(7), pp.549-563.

Gazetas, G., 1987. Seismic response of earth dams: some recent developments. Soil Dynamics and Earthquake Engineering, 6(1), pp. 3-47.

Han, B., Zdravkovic, L., Kontoe, S. and Taborda, D.M., 2016. Numerical investigation of the response of the Yele rockfill dam during the 2008

Wenchuan earthquake. Soil Dynamics and Earthquake Engineering, 88, pp.124-142.

Idriss, I., Mathour, J. & Seed, H., 1974. Earth dam-foundation interaction during earthquakes. Earthquake Engineering and Structural Dynamics, Volume 2, pp. 313-323.

Kontoe, S., Pelecanos, L. and Potts, D., 2013. An important pitfall of pseudo-static finite element analysis. Computers and Geotechnics, 48, pp.41-50.

Kramer, S.L., 1996. Geotechnical earthquake engineering prentice hall. Upper Saddle River, NJ.

Lo, E. and Pelecanos, L., 2018. Comparison of shear-beam and dynamic finite-element modal analysis of earth dams. 20th Biennial BDS (British Dam Society) Conference, 13-15 September 2018, Swansea, UK.

Pelecanos, L., 2013. Seismic response and analysis of earth dams, London, United Kingdom: PhD thesis, Imperial College London.

Pelecanos, L., Kontoe, S. and Zdravkovic, L., 2012a. Static and dynamic analysis of La Villita Dam in Mexico. In 2nd International Conference on Performance-Based Design in Earthquake Geotechnical Engineering.

Pelecanos, L., Kontoe, S. and Zdravković, L., 2012b. Numerical Analysis of the Seismic Response of La Villita Dam in Mexico. In Dams: Engineering in a Social and Environmental Context (pp. 120-130). ICE Publishing.

Pelecanos, L., Kontoe, S. & Zdravkovic, L., 2013a. Numerical modelling of hydrodynamic pressures on dams. Computers and Geotechnics, Volume 53, pp. 68-82.

Pelecanos, L., Kontoe, S. and Zdravkovic, L., 2013b. Assessment of boundary conditions for dam-reservoir interaction problems. In 4th International Conference on Computational Methods in Structural Dynamics

Pelecanos, L., Kontoe, S. & Zdravkovic, L., 2015. A case study on the seismic performance of earth dams. Geotechnique, 65(11), pp. 923-935.

Pelecanos, L., Kontoe, S. & Zdravkovic, L., 2016. Dam-reservoir interaction effects in the elastic dynamic response of concrete and earth dams. Soil Dynamics and Earthquake Engineering, 82 (2016), pp. 138-141.

Pelecanos, L., Kontoe, S. and Zdravkovic, L., 2017, Steady-state and transient dynamic visco-elastic response of concrete and earth dams due to dam-reservoir interaction. 6th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN)

Smart Dams and Reservoirs

Pelecanos, L., Kontoe, S. & Zdravkovic, L., 2018a. The effects of dam-reservoir interaction on the nonlinear seismic response of earth dams. Journal of Earthquake Engineering (DOI: 10.1080/13632469.2018.1453409).

Pelecanos, L., Kontoe, S. and Zdravkovic, L., 2018b, The effects of nonlinear dam-foundation interaction on the seismic response of earth dams. 16th European Conference on Earthquake Engineering, Thessaloniki, Greece.

Pelecanos, L., Kontoe, S. and Zdravkovic, L., 2019a, Seismic response of earth dams in narrow canyons. 7th International Conference on Earthquake Geotechnical Engineering (7 ICEGE). 17-20 June Rome, Italy.

Pelecanos, L., Kontoe, S. and Zdravkovic, L., 2019b, Nonlinear seismic response of earth dams due to dam-reservoir interaction. 17th European Conference on Soil Mechanics and Geotechnical Engineering (XVII ECSMGE). 1-6 September, Reykjavik, Iceland.

Saleh, S. and Madabhushi, S.P.G., 2010. Response of concrete dams on rigid and soil foundations under earthquake loading. Journal of Earthquake and Tsunami, 4(03), pp.251-268.

Shire, T., Pelecanos, L., Bo, H. and Taylor, H., 2013. Current research in embankment dam engineering at Imperial College London. Dams and Reservoirs, 23(1), pp.25-28.

Wolf, J., 1985. Dynamic soil-structure interaction. Prentice Hall, Inc.

Wolf, J.P., 2003. The scaled boundary finite element method. John Wiley & Sons.

Zhao, C. and Valliappan, S., 1993. A dynamic infinite element for three-dimensional infinite-domain wave problems. International journal for numerical methods in engineering, 36 (15), pp.2567-2580.