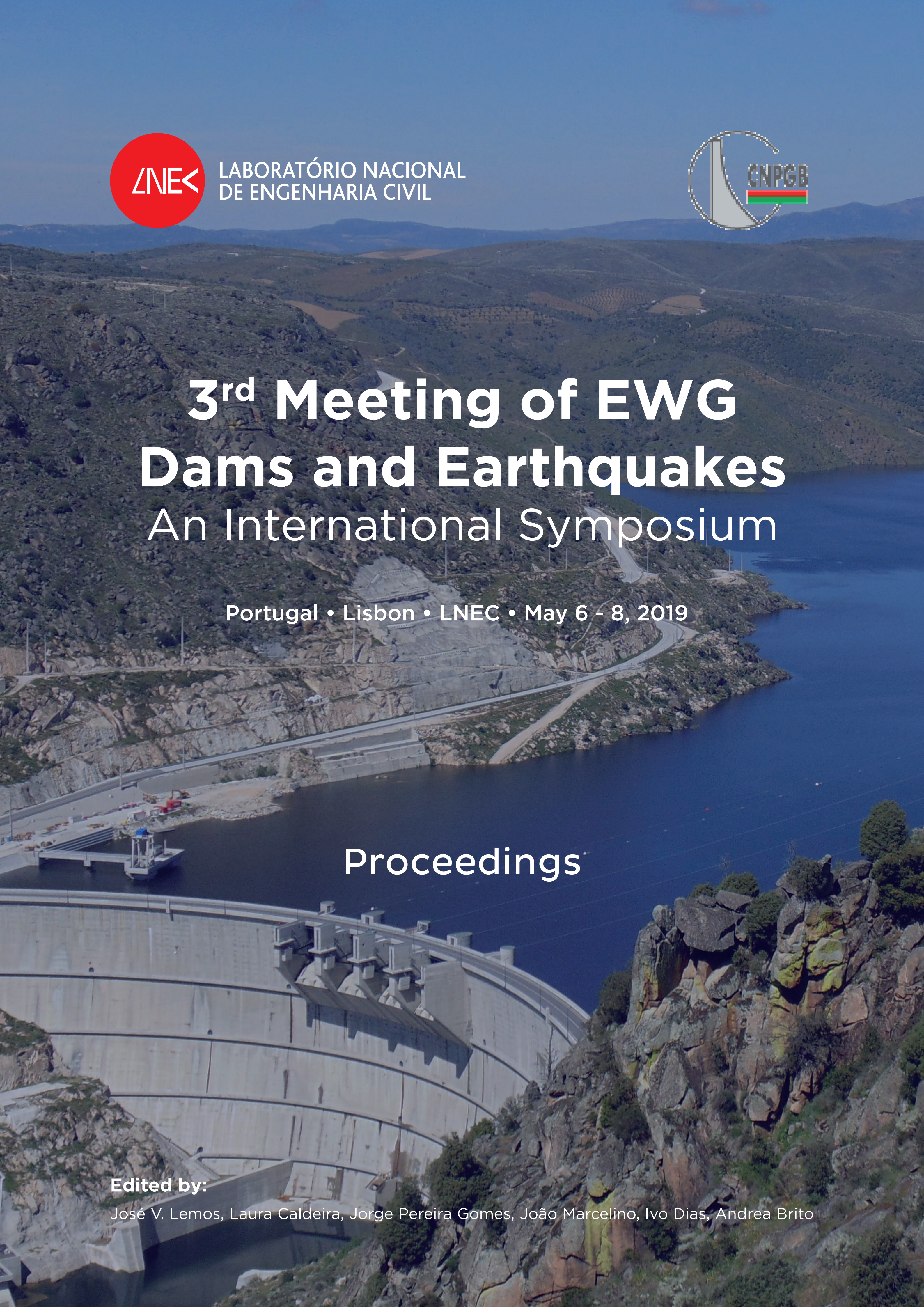

LABORATÓRIO NACIONAL
DE ENGENHARIA CIVIL

CNPGB

3rd Meeting of EWG Dams and Earthquakes

An International Symposium

Portugal • Lisbon • LNEC • May 6 - 8, 2019

Proceedings

Edited by:

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Divisão de Divulgação Científica e Técnica
AV DO BRASIL 101 • 1700-066 LISBOA
e-e: livraria@lnec.pt
www.lnec.pt

Publisher: LNEC

Collection: National and international meetings

Série: RNI 105

1st. edition: 2019 (pdf)

Descriptors: Seismic response of structures / Concrete dams / Embankment dams / Monitoring / Dams safety / / International congress

Descritores: Solicitação sísmica de estruturas / Barragens de betão / Barragens de aterro / Monitorização / Segurança de barragens / Congresso internacional

CDU 627.82.042.7(063)(100)
ISBN 978-972-49-2308-6

Preface

The 3rd meeting of the ICOLD European Club Working Group "Dams and Earthquakes" took place at LNEC, Lisbon, Portugal, on 6-8 May 2019. Following the very successful events in St. Malo and Rome, this meeting brought together a group of international experts to discuss the multiple challenges that earthquakes pose to dams. Recent advances on dynamic monitoring techniques coupled with new developments in material and structural modelling are making available to engineers powerful tools that need to be tested, validated and widely disseminated. The digital proceedings contain a collection of papers that reflect the state-of-the-art on the analysis and safety assessment of concrete and embankment dams under seismic actions. We would like to acknowledge our appreciation to the authors for their effort in preparing these contributions and their willingness to share their research accomplishments. We would also like to express our gratitude to the members of the Scientific Committee who reviewed these papers.

The Organizing Committee

Themes

- Definition of seismic hazard for dams
- Measurements of response of concrete or embankment dams under earthquakes
- Dynamic monitoring and testing of dams
- Comparison of numerical models with dynamic field measurements
- Qualification of equipment under seismic loading

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EMBANKMENT DAMS

Identification of dynamic soil properties of dam materials by in-situ testing with seismic geophysical methods

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Keywords: Identification of dynamic soil properties, geophysical testing, case study

Abstract. *After Swiss regulations, all existing large dams in Switzerland had to be assessed in respect of earthquake safety for revised design criteria by the year 2013. The present paper documents the case study of Marmorera embankment dam in Switzerland of 91 m height in respect of parameter identification for numerical earthquake assessment. In order to obtain in-situ dynamic properties of the dam, seismic geophysical measurements had been performed to measure shear wave velocities of the dam body and the foundation. The paper gives an introduction to the structure of the dam and presents the geophysical testes performed and their results. The measured shear wave velocities are compared to experience from other studies taken from literature. Further, it is shown how the initial shear modulus* G_{max} *of the dam material was derived and implemented in the numerical model for linear equivalent analysis of earthquake behaviour.*

1 INTRODUCTION

According to the guidelines of the Federal Office of Energy - Section Dams [1], all dams in Switzerland were inspected for their earthquake safety under federal supervision by 2013. This also applies to the Marmorera embankment dam operated by the ewz (Electricity Works Zurich). The dam is located in Graubunden in the Surses region below the Julier Pass in the Swiss Alps The dam is classified as large dam of category I. Construction work started in year 1949 with the first impounding in year 1954.

The Marmorera dam is a zoned earth fill dam with core sealing, filter layer and supporting shell. Only local earth materials consisting of moraine, landslide material and suspended debris were used for the dam body. During the construction of the dam in the late 1940's early 1950's, the sealing core was compacted with sheep foot compaction rollers and the supporting body was washed in with high-pressure water jets [2]. On the upstream side, a protective layer of coarse block material against wave impact was applied. The downstream side of the dam is covered with humus and is greened. The dam foot areas are stabilized with blocks of rock. An aerial photograph and the main cross-section at profile +226 are shown in Figure 1 and Figure 2 respectively.

With a maximum dam height of 91 m and a reservoir volume of approximately 60 million m^3, the Marmorera dam belongs to large dams of category I according to Swiss regulations [1]. Table 1 provides an overview of the key figures for the dam. Due to the size of the dam, increased requirements need to be fulfilled in respect to earthquake safety and the

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verification of dam safety. This includes, for example, the requirement for measurements of dynamic soil parameters and the verification of the dam using numerical methods with time history analysis [1].

Figure 1: Areal view of Marmorera dam

Table 1: Characteristics of Marmorera dam

Characteristics	Value
dam type	zoned earth fill dam with core sealing
maximum dam height	91 m
crest length	400 m
crest elevation	1684.40 masl
foundation elevation	1593.40 masl
width at crest	12 m
width at foundation	400 m
slope inclination upstream	variable min. 1 V : 2.1 H
slope inclination downstream	variable min. 1 V : 1.63 H
dam body volume	2.7 Mm^3
reservoir level	1680.00 masl
volume of reservoir	ca. 60 Mm^3

For the majority of geotechnical soil parameters, extensive investigations from the construction as well as from the operation period of the dam are available. For the dynamic soil parameters, the earthquake testing focuses on specifically performed field tests with geophysical measurements of the dam. By means of seismic tomography, a spatial model of the shear wave velocity distribution of the dam and of the foundation is developed. The present article deals with the geophysical measurements of the dam and describes the calibration of the dynamic shear modulus for the numerical calculation model of the dam.

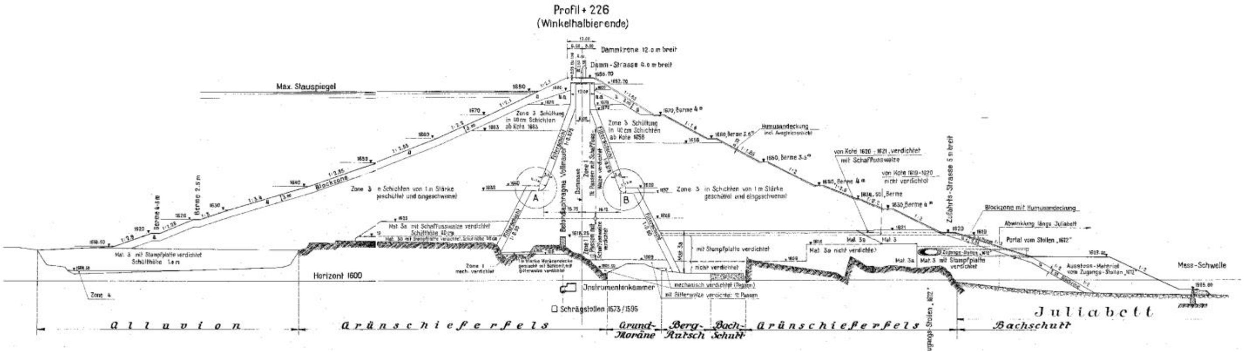

Figure 2: Main cross section of Marmorera embankment dam at profile +226

2 GEOPHYSICAL MEASURING PROGRAM

Already in the 1940's, geophysical investigations by means of P-wave seismic refraction were carried out to determine the rock horizon and the thickness of the soil. However, the old measurement results are hardly meaningful for the required earthquake analysis. For this reason, roXplore gmbh carried out a comprehensive seismic-geophysical investigation program in 2012 [3]. Seismic refraction and MASW (Multichannel Analysis of Surface Waves) from the dam surface, tomography measurements from the dam surface to the inspection galleries inside the dam and H/V measurements on the dam surface were carried out. An overview of the measurement profiles is shown in Figure 3. Figure 4 shows parts of the geophone layout on the dam crest and in the inspection galleries as well as the shaker for excitation of harmonic shear wave sweeps.

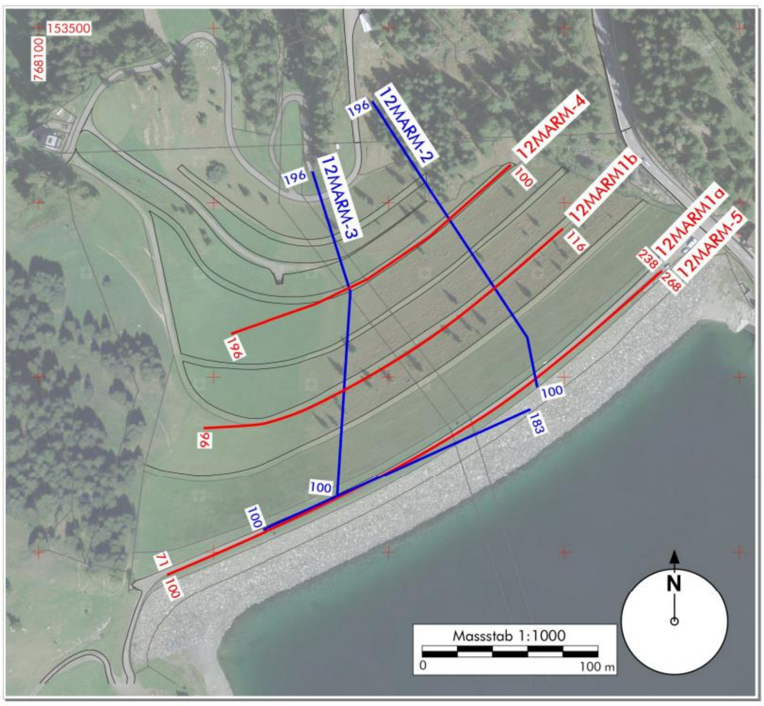

Figure 3: Layout of measurement profiles [1], red - arrays on dam surface, blue arrays in inspection galleries in the inner dam body

Figure 4: Seismic geophysical measurements, left: excitation of shear waves on the dam crest with shaker and part of geophone array mounted on a landstreamer system; right: geophone array in the inspection gallery in the inner dam body [3]

2.1 Seismic tomography

A total of 4 tomographic profiles were recorded, two profiles in the dam axis and two profiles in the dam cross section. The tomographic measurements are possible because the dam in the dam axis and on the downstream side perpendicular to the dam axis has several inspection galleries. The inspection galleries run in the floor plan according to the measuring profiles 12MARM-1a, 12MARM-2 and 12MARM-3, as shown in Figure 3. The wave excitation was performed at the dam surface, while the receivers were arranged in the inspection galleries (see Figure 4). Selected results of the tomography measurements are shown in Figure 5 to Figure 7.

The two tomographic profiles in the dam cross-section (Figure 5 and Figure 6) show a relatively homogeneous structure of the dam body. The shear wave velocities vary between 500 m/s and 800 m/s. Figure 5 clearly shows the bedrock surface with a shear wave velocity of approx. 2500 m/s, as this inspection gallery of the cross-section 12MARM-2 runs exclusively under the dam body in the bedrock. The tomography also provides indications of a geological disturbance in the rock due to reduced shear wave velocities.

There is one issue noticeable about the results of the tomographic cross section measurements. In the shear wave velocity distributions of the downstream dam body (e.g. see Figure 6), there is no obvious difference in shear wave velocity for dam core material and the shell material. This phenomenon can be mainly explained by the similar geological origin and characteristics of the moraine and slope debris material used and the similar construction process. A comparison of the grain size distribution shows that all materials have a well graded grain size distribution and only the core zone has a slightly larger proportion of fine content. The general well graded grain structure with sand, gravel and stones is quite similar for core and shell material. The relative densities of all materials are high due to the compacted placement. The in-situ densities show only minor differences between materials.

Figure 7 shows the tomographic longitudinal section of the dam along the dam crest (12MARM-1a in Figure 3). The measured shear wave velocities show relatively consistent values compared to the tomographic cross-sections. The bedrock surface on the east side of the dam body (Figure 7 left area) cannot be reliably determined due to layout of the inspection gallery and the limited space for the geophone array.

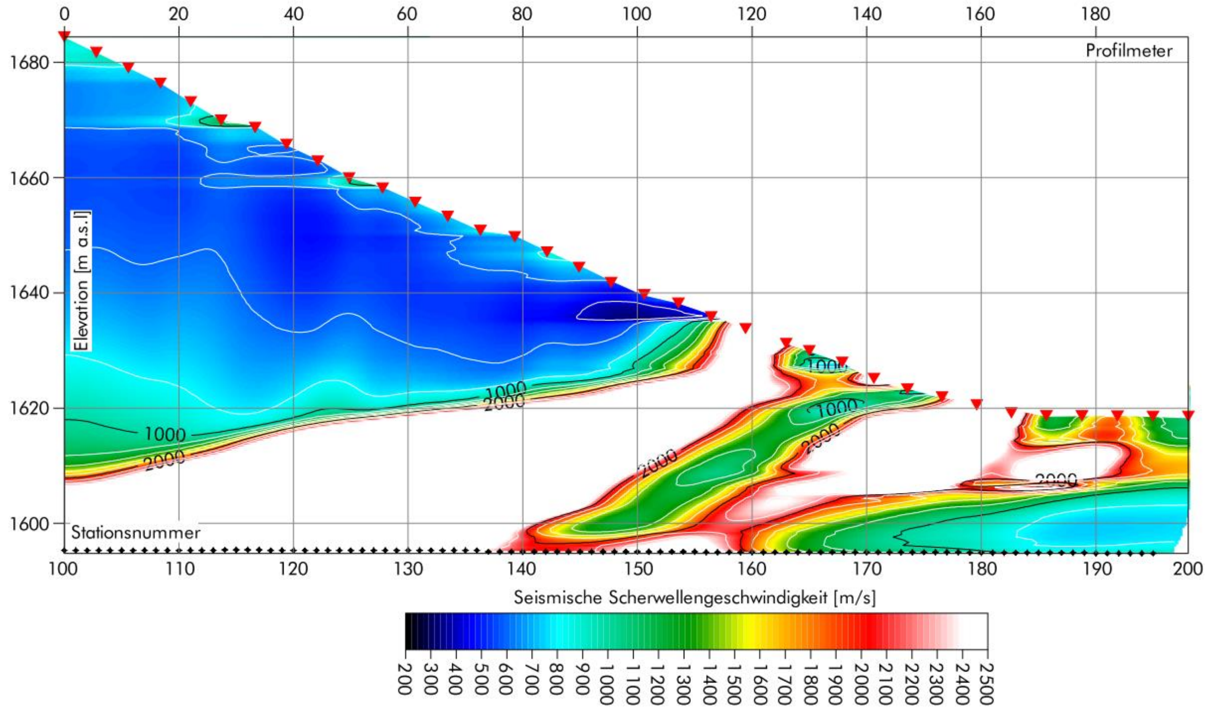

Figure 5: Tomography results: shear wave velocity distribution on the downstream side in section 12MARM-2 (see Figure 3) with excitation on the dam surface and measurements in the inspection gallery at elevation 1595 masl located in the bed rock [3]

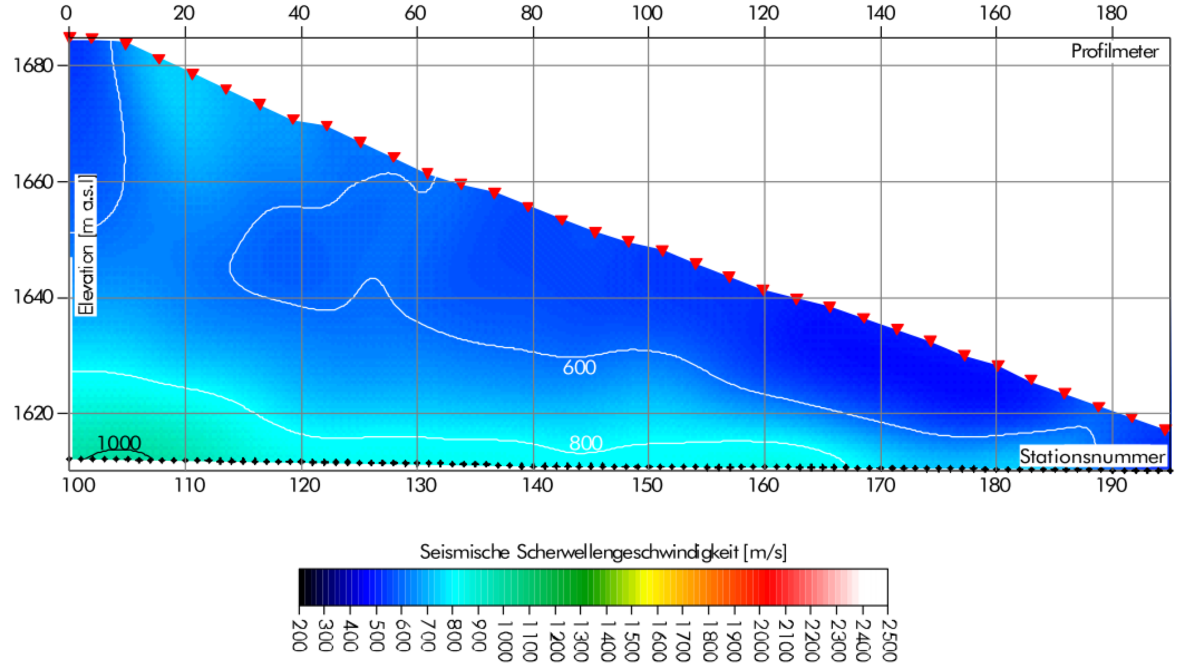

Figure 6: Tomography results: shear wave velocity distribution on the downstream side in section 12MARM-3 (see Figure 3) with excitation on the dam surface and measurements in the inspection gallery at elevation 1615 masl [3]

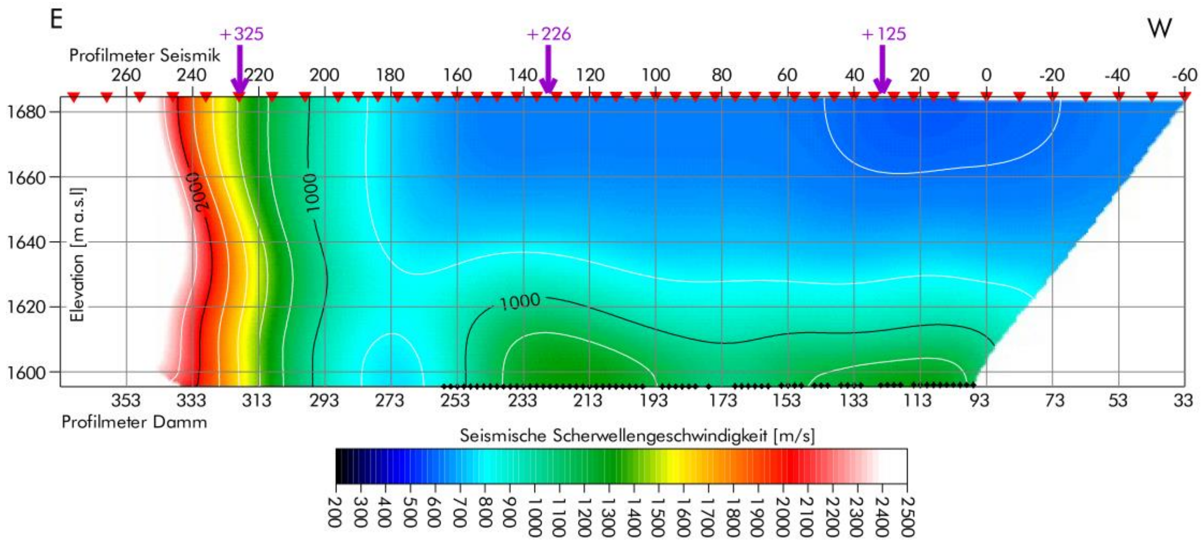

Figure 7: Tomography results: shear wave velocity distribution in dam axis in section 12MARM-1a (see Figure 3) with excitation on the dam crest and measurements in inspection gallery at elevation 1595 masl [3]

2.2 Seismic refraction

The results of seismic refraction are summarized in Figure 8 and Figure 9. The shear wave velocities of the dam body are in the range between 300 m/s and 1000 m/s. During the measurement on the berm at elevation 1640 (Figure 9), the bedrock surface with shear wave velocities of approx. 2000 m/s is clearly visible. From seismic refraction, the shear wave velocity of the core material along the dam axis measured from the dam crest at elevation 1684 masl is smaller as the shear wave velocity of the shell material measured froim the berm at elevation 1640 masl.

The lower measured shear wave velocities of seismic refraction at the dam surface compared to the results of the tomography measurements are due to the higher resolution of seismic refraction near the surface.

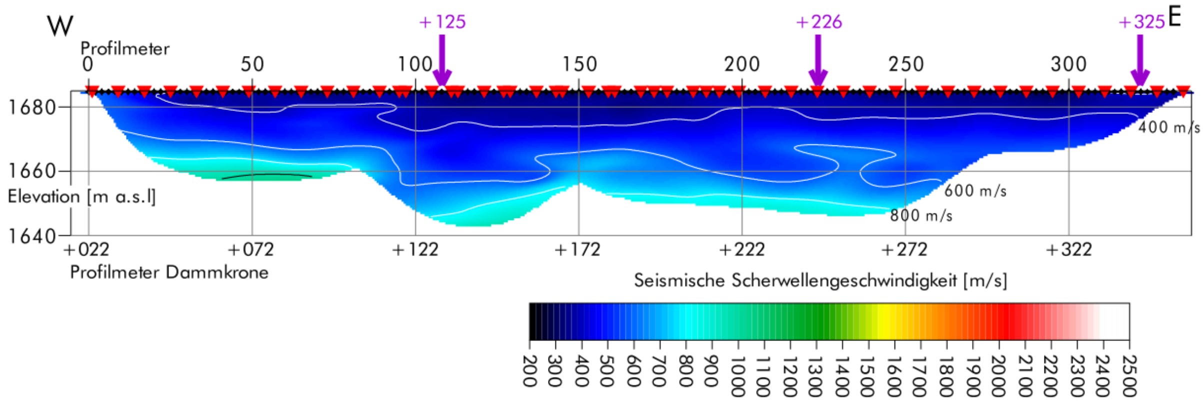

Figure 8: Results from seismic refraction: shear wave velocity distribution with measurements on the dam crest at elevation 1684 masl along the dam axis (section 12MARM-5 in Figure 3) [3]

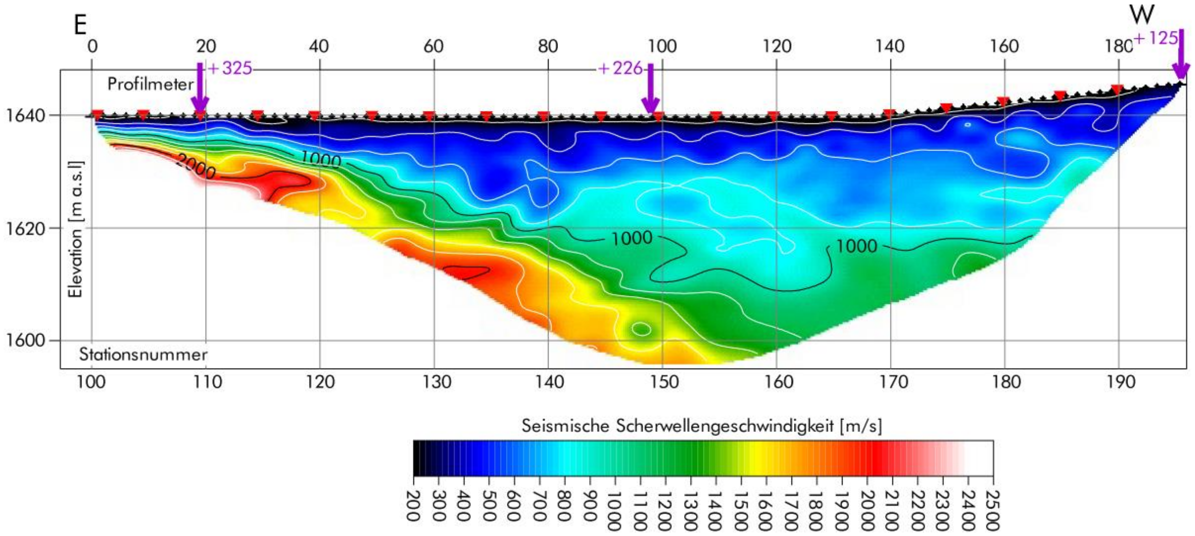

Figure 9: Results from seismic refraction: shear wave velocity distribution with measurements parallel to the dam axis on berm at elevation 1640 masl (section 12MARM-4 in Figure 3) [3]

2.3 MASW measurements

The following Figure 10 and Figure 11 give selected results of MASW measurement on the dam crest at elevation at 1684 masl and on the berm at elevation at 1640 masl respectively. The results also from other measuring stations show some variability with a tendency to high shear wave velocities. The values of v_{s30} range between 580 m/s to 660 m/s. Based on MASW measurement the core and shell material show no obvious difference in shear wave velocity. The values in depth below 20 m reaches values of v_s up to 1000 m/s and above with shear stiffness comparable to rock. The v_s results from MASW measurements are higher than from seismic refraction.

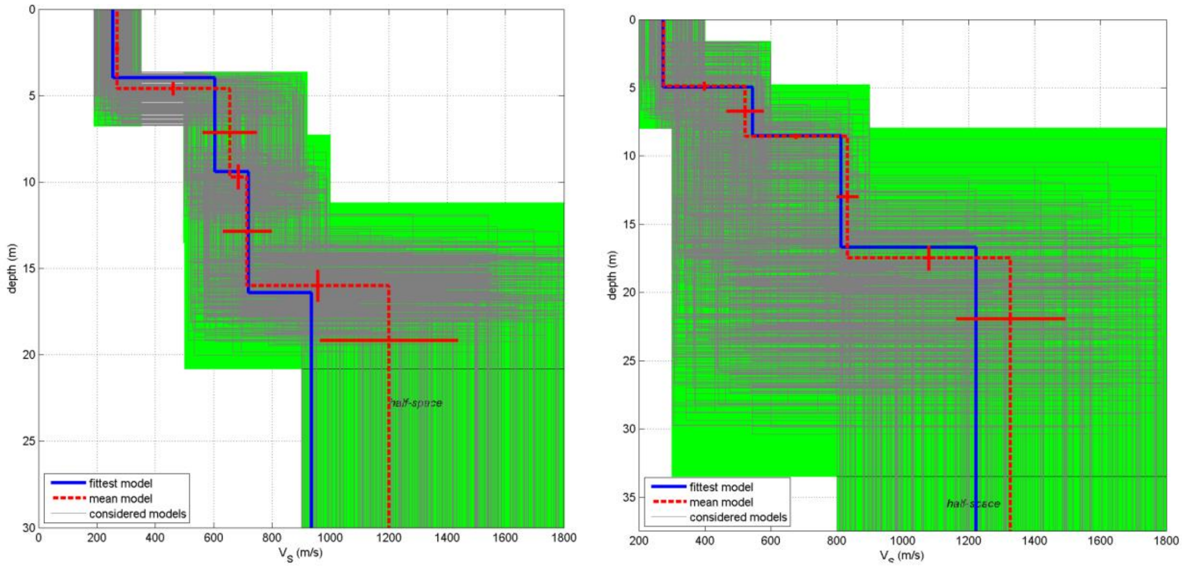

Figure 10: MASW measurements on dam crest al elevation 1684 masl: left - station 173 (v_{s30} = 614 m/s); right - station 176 (v_{s30} = 629 m/s) [3]

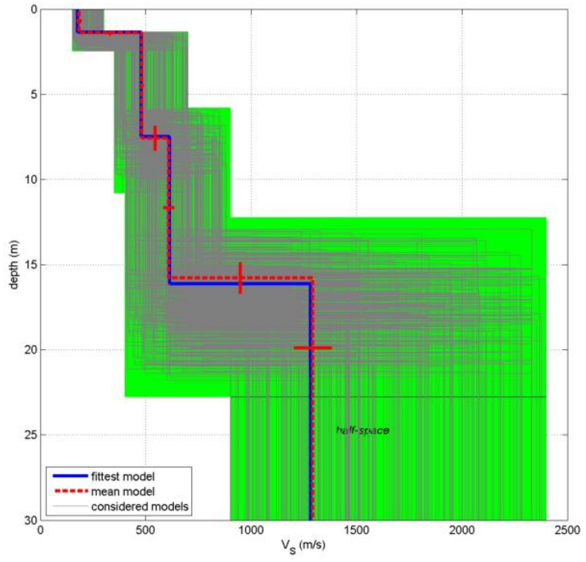

Figure 11: MASW measurements on berm at elevation 1640 masl: left - station 167 (v_{s30} = 661 m/s); right - station 189 (v_{s30} = 587 m/s) [3]

3 COMPARISON OF SHEAR WAVE VELOCITIES TO OTHER DATA

The geophysical investigations were used to measure the shear wave velocities of the dam body and the bedrock on the downstream side of Marmorera dam. The measurements generally show consistent results. Based on the results from seismic refraction, the shear wave velocities at 20 m depth are about $v_s \approx 600$ m/s and based on the tomography measurement at 80 m depth about $v_s \approx 900$ m/s.

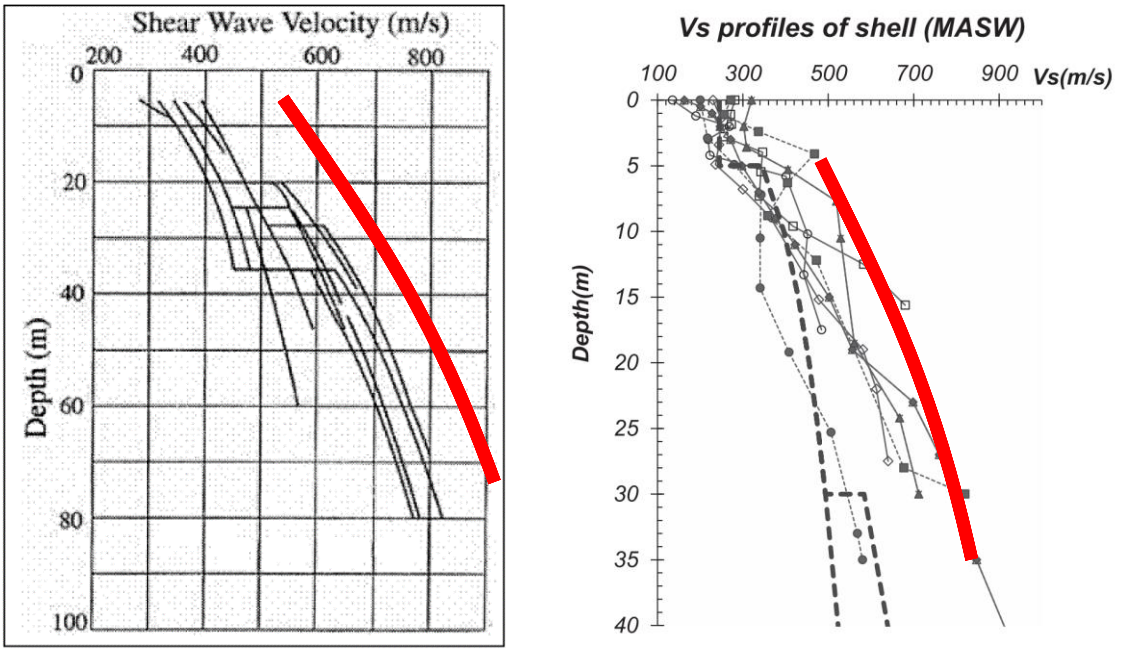

Figure 12: Shear wave velocities of dams, left from [4] and right from [5] in comparison to Marmorera data in red

The shear wave velocities of Marmorera dam body are higher than the upper bound of shear wave velocities documented by Sawada & Takahashi [4] based on Japanese data. The Marmora measurements correlate nicely with measurements by Park & Kishida [5] from 28

Korean embankment dams. They commented, that the Japanese data from Sawada & Takahashi [4] underestimate the shear wave velocities of dam shell material. This conclusion can be supported from the measurements of Marmorera dam. The comparison of data from Marmorera dam to data from the other authors is shown in Figure 12.

4 H/V MEASUREMENT

Here, it should be noted that the H/V measurements on the dam surface did not yield any reasonable results. The measured H/V maxima could not be assigned to any eigenperiod of the dam gained from numerical analysis, even considering the directivity of wave orientation in the dam body. The measured eigenperiods are too large, by a factor of 3 to 5. The method H/V according to Nakamura [6] applies to horizontally layered half-space. It is assumed that the correlation of H/V measurement results is poor to dam eigenperiods due to the topography of the dam. Based on experience from Marmorera, the favourable H/V method cannot be transferred to dam structures for easy eigenperiod measurements.

5 CALIBRATION OF MAXIMUM SHEAR MODULUS

The maximum shear modulus G_{max} and the shear wave velocity v_s are directly related with the influence of density:

$$G_{max} = v_s^2 \cdot \rho \tag{1}$$

Here it is assumed that the shear strains caused by shear waves from geophysical measurements excitation are in a very small strain range ($\gamma < 10^{-6}$). According to geotechnical reports, the density of the dam body materials at Marmorera dam averages around 2300 kg/m^3.

According to Seed and others [7], [8], the maximum shear modulus G_{max} can be represented as a function of the mean effective stress σ_m'. The correlation is given as follows:

$$G_{max} = 220\ K_2\ (\sigma_m')^{0.5} \quad [\mathrm{kN/m^2}] \tag{2}$$

The parameter K_2 is calibrated by means of the shear wave velocity from geophysical measurement results and stress analysis. Based on the analysis of the initial stress condition of the dam with elastic-plastic material behaviour (Mohr-Coulomb), the distribution of the mean effective stresses σ_m' in the dam body is shown in Figure 13. The red rectangle corresponds to the tomography measurement in Figure 6. This results in stress state σ_m' of approx. 900 kN/m^2 to 1000 kN/m^2 for the effective stress with an empty reservoir in the middle of the dam at a foundation level of approx. 80 m depth. Based on the stress analysis with the Finite-Element-Method (Figure 13) and the distribution of the shear wave velocity (e.g. Figure 6 and Figure 8), a value of $K_2 = 240$ was determined ($z = 20$ m - $\sigma_m' = 240$ kN/m^2 - $v_s = 600$ m/s; $z = 80$ m - $\sigma_m' = 970$ kN/m^2 - $v_s = 850$ m/s). A higher weight is given to results from seismic refraction than to MASW. Figure 14 shows the mean effective stress σ_m', shear wave velocity v_s and the maximum shear modulus G_{max} in the dam body as a function of the depth z under the dam crest according to the formulation of Seed & Idriss [7] for a value $K_2 = 240$. This K_2 value is consistent from laboratory test result in Switzerland for dense alpine moraine material, see [9].

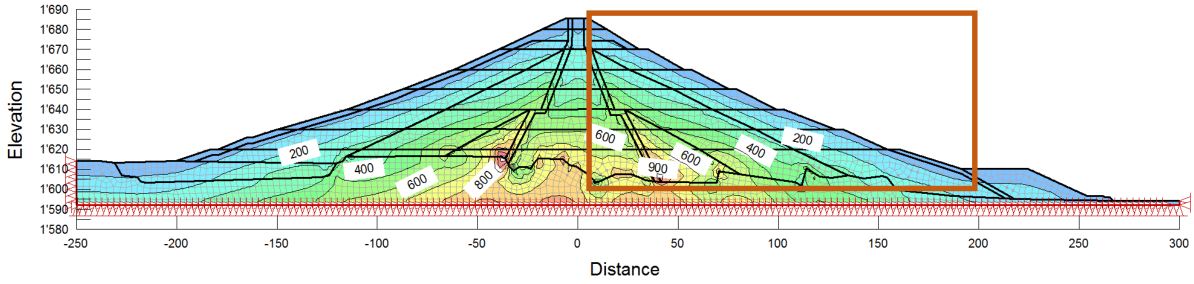

Figure 13: Numerical stress analysis with FEM [9], initial stress state in the dam body before impounding, mean effective stress σ_m' [kN/m^2], red marked area of seismic tomography measurements Figure 6

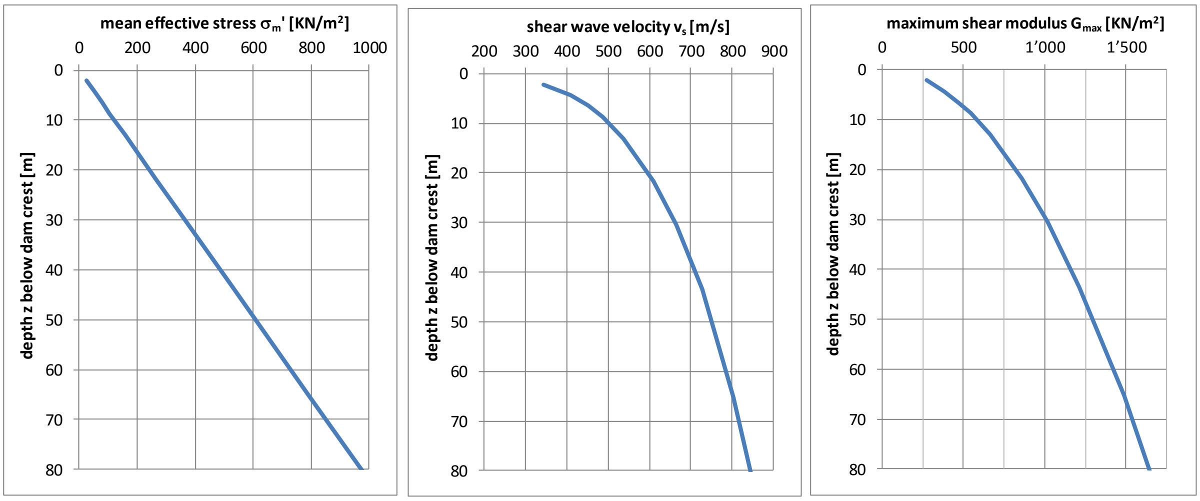

Figure 14: Mean effective stress σ_m', shear wave velocity v_s and maximum shear modulus G_{max} in the dam body depending on depth from dam crest

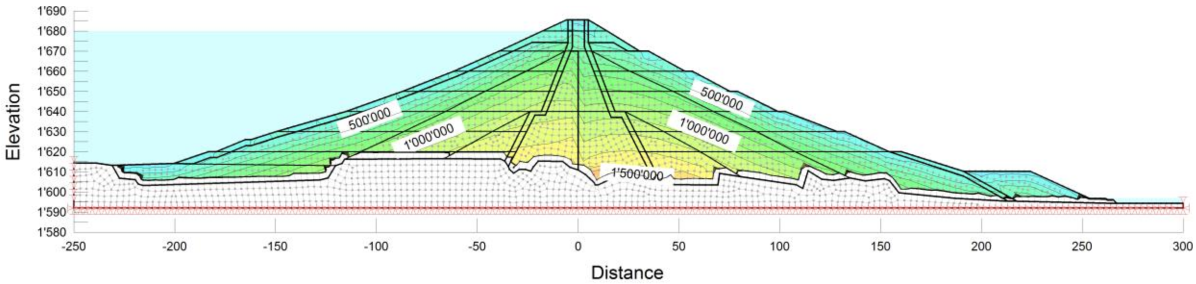

Figure 15: Distribution of maximum shear modulus G_{max} [kN/m^2] in the dam body before earthquake time history analysis [10]

The stress dependence of the maximum shear modulus G_{max} is defined in the numerical model for the initial state of the dynamic analysis. Figure 15 shows the distribution of the maximum shear modulus G_{max} at the beginning of the earthquake time history analysis using the program QUAKE/W of the software system GeoStudio 2012. For a comprehensive earthquake assessment, further dynamic soil parameters need to be defined. These include the strain-dependent linear-equivalent parameters of shear modulus and damping ratio for soil and rock. For the determination of the normalised strain dependent shear modulus curves, which are attached to the maximum the shear modulus G_{max}, and the corresponding damping curves, values are taken from literature, [9] and [11] since no specific cyclic laboratory tests were performed for Marmorera dam.

6 CONCLUSION

By means of seismic-geophysical measurements, such as tomography, seismic refraction and MASW, the distribution of the shear wave velocity in the dam body of the Marmorera dam was examined in more detail. Based on the shear wave velocity distribution, the stress dependent maximum shear modulus G_{max} was correlated. As a result, the shear wave velocities of the dam body material at Marmorera dam are consistent on the higher side compared to values from the literature and thus the dam has a high initial shear stiffness.

The initial shear modulus has a large influence on the earthquake behaviour of the dam, as it decisively influences the amplification of the earthquake excitation in the dam body from the foundation to the crest. The geophysical measurements performed are very well suited to determine the maximum shear modulus of the dam materials. This knowledge reduces the uncertainty in numerical earthquake calculations of soil materials. Measurements of H/V ratio even with consideration of wave field orientation did not gain reasonable results to determine fundamental dam periods.

In summary, it is recommended to measure the shear wave velocities of dam materials of existing dams with geophysical methods in order to specify the dynamic characteristics of G_{max} for numerical calculations. Also for new to be build dam, geophysical measurements can be performed after construction in order to verify numerical analysis performed and assumptions made initially.

ACKNOWLEDGEMENTS

The authors would like to thank Andreas Siegfried and Patrick Saudan from ewz - Electricity Works Zurich - for the very good cooperation and the permission to publish the data. Special thanks goes to Jan Laue from the Technical University Lulea Sweden for his support and cooperation in the project. Finally, Jost A. Studer, who unfortunately was not able to experience the completion the project, is remembered here.

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