INTERNATIONAL SOCIETY FOR
SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING

This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
© 2019 Associazione Geotecnica Italiana, Rome, Italy, ISBN 978-0-367-14328-2

Advanced numerical modeling of Aratozawa dam response under Miyagi 2008 strong earthquake

M. Kham
EDF R&D, Saclay, France

P. Kolmayer
EDF CIH, Chambéry, France

N. Matsumoto
Japan Dam Engineering Center, Japan

ABSTRACT: A methodology is proposed for estimating the stability of embankment dams against liquefaction under seismic loadings, taking into account the cyclic plastic hardening/softening of soils (Hujeux's model) and air bubbles occluded in pore water for the assessment of pore pressure build-up (Boutonnier's model). This advanced methodology was applied to simulate the response of Aratozawa dam submitted to the 1g earthquake in 2008, using Code_Aster finite element software. The improved model taking occluded air into account leads to a better prediction of the dam response, particularly of the pore pressure build-up in the core than using a perfectly saturated model.

1 INTRODUCTION

The evolving regulatory context with increasing seismic levels for hydraulic structures will affect in the coming years all the French dam owners. For EDF, operator of about 200 large dams, the development of best-estimate methods of calculation releasing safety margins became a major industrial and economic issue. Hereafter, a methodology is proposed for estimating the stability of embankment dams against liquefaction under seismic loadings, taking into account air bubbles occluded in soils for the assessment of pore pressure build-up (Boutonnier's model). The methodology is applied to the case of Aratozawa dam, supplied by a collaboration between the Japanese and French committees of the International Commission of Large Dams. This well instrumented rockfill dam was submitted to a strong shaking in 2008 up to 1g. The advanced methodology using Boutonnier's model was applied to simulate the response of the dam, and compared to records, to a fully incompressible water saturated model and to a perfectly drained model (purely mechanical model). The influence of the vertical component of the input motion is also investigated.

2 PHYSICAL MODELS

The behavior of earth dams under earthquake is mainly determined by the complex coupling between the behavior of the solid phase constituted by a granular material and that of the fluid phases constituted by a mixed of air and water. Since the stability of the dam is mainly related to pore pressure buildup which by nature is determined by the aforementioned physical coupling, a good predictive model should incorporate precise constitutive models of both the solid and the fluid phases. Such models are presented in the following.

2.1 *Hujeux's model for soil*

The constitutive soil model from Centrale Supélec, France, known as Hujeux's model (Lopez-Caballero, 2007) is used. Hujeux's model is a unified formulation able to take into account the behavior of both sand and clay for a large range of deformations. The model is written in terms of effective stress in the generalized standard framework of non-associated plasticity. The characteristics of the model are the following:

- It encompasses a non-linear elastic relationship for Young's modulus of the type:

$$E = E_{\max}\left(\frac{p\prime}{p_{réf}}\right)^{n} \tag{1}$$

- where E_{max} is the small strain Young's modulus, $p\prime$ the mean effective stress, and $p_{réf}$ and n two constant parameters of the model;
- Anisotropic irreversible phenomena are represented by four coupled elementary plastic mechanisms: three plane-strain deviatoric mechanisms in three orthogonal planes and one isotropic mechanism The hardening of the deviatoric mechanisms is based on the deviatoric and volumetric plastic strain and only the volumetric strain for the isotropic one;
- A Coulomb-type failure criterion and the critical state concept are incorporated;
- The cyclic behavior is based on a kinematical hardening of the state variables from the last load reversal;

Hujeux's model capability to predict undrained soil behavior and liquefaction of earthdams under static or transient loadings was established by many studies. Refer to Lopez-Caballero (2018).

2.2 *Boutonnier's model for the fluid phase*

A good prediction of the compressibility of the solid phase in undrained conditions is insufficient if a good prediction of the fluid phase compressibility is not available. To this aim, Boutonnier's model is used herein. This model is based on the representation of the behavior of a unit volume of fluid made of air bubbles occluded in water. In undrained condition, since there is no mass variation of fluid, a relation between water pressure u_w and saturation degree S_r can be derived as following taking into account air dissolution and diffusion into water:

$$S_r(u_w) = \frac{1}{1 - h + \frac{1-S_{re}+hS_{re}}{S_{re}} \cdot \frac{s_{bm}+P_{atm}-u_{wg}}{u_w+s_{bm}+P_{atm}-u_{wg}}} \tag{2}$$

with h (=0.02) Henry's coefficient for air dissolution in water, $s_{bm} = \frac{2T_c}{r_{bm}}$ where T_c (≅73.5 10^{-3} N/m) is the air-water surface tension, r_{bm} (≅10μm) the occluded air radius, P_{atm} (=10^{+5} Pa) is the atmosphere air pressure, u_{wg} (≅2.3 kPa) the saturated vapor pressure of Kelvin's law, and S_{re} the residual saturation degree at $u_w=0$ to be identified. Subsequently, the air/water mixture equivalent compressibility c_f can be derived as following:

$$c_f = \frac{1}{K_f} = c_w + \frac{1 - S_r(u_w) + hS_r(u_w)}{u_w + s_{bm} + P_{atm} - u_{wg}} \tag{3}$$

with c_w (≅5.10^{-10} Pa^{-1}) is the water compressibility,:

This model has the advantage to be quite simple and easy to calibrate, but also to allow a good assessment of the compressibility of the air-water mixture as far as fine grained soils compacted in the wet side of Proctor Optimum are concerned (which is the case of earthdams). Refer to Boutonnier (2018).

3 APPLICATION TO ARATOZAWA DAM

This test-case was supplied by a collaboration between the Japanese and French committees of the International Commission of Large Dams. In this framework, a benchmark was organized involving both French and Japanese teams. The results of this benchmark were presented at a symposium organized at Saint-Malo in 2016 (Refer to Fry & Matsumoto, 2018).

3.1 *Description of Aratozawa dam*

The Aratozawa dam is a central clay core rockfill dam located in the Iwate Prefecture of Japan. It was constructed mainly for irrigation and flood control purposes. It is a 74.4m high dam with 1:2.7 upstream and 1:2.1 downstream slide slopes, a crest length of 413.7m and crest width of 10m. The dam body consists of 5 zones: core, filter, transition, inner rockfill and outer rockfill zones. The core materials are clay mixed with gravel with a plasticity index IP equal to 32%. As it is considered as fully coupled, the permeability coefficient of the core is 10^{-5}cm/s. For the remaining zones including filter, transition and rockfill, they are considered as perfectly drained.

The Iwate-Miyagu Nairiku earthquake of magnitude M_w=7.2 took place in June 14 of 2008 at 8:43am. The epicenter was 8 km below south-western Iwate Prefecture in Japan and 15 km from the Aratozawa dam. The largest peak acceleration at the bottom gallery for the main shock was 10.24 m/s^2 (Figure 1-b), while a deamplification to 5.25 m/s^2 was recorded in the dam crest, indicating that the dam presented high nonlinear behavior to the earthquake. The settlement recorded at the crest was about 40 cm. Measurements of pore pressure build-up in the core after the main shock are available (Figure 2).

3.2 *Setting of the numerical model*

A finite element model of Aratozawa dam using Code_Aster is considered in this work. As aforementioned, the model is 2D and hydro-mechanically fully coupled in the core, whereas the rockfill shoulders are considered perfectly drained. The mesh is shown in Figure 3. The first step consists to numerically construct the dam layer by layer followed by an impounding in the upstream. Verifications of the initial state before the dynamic calculation consist of:

- Adequacy of the predominant frequency of dam measured at 2.9Hz (Ohmachi, 2008);
- Adequacy of the static pore-pressure profile in the core;

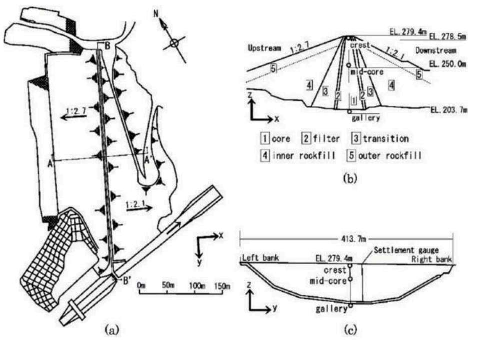

Figure 1. (a) View from above, (b) cross section A-A' and (c) cross section B-B' of the Aratozawa dam with seismometers located at the crest, mid-core and gallery (Ohmachi and Tahara, 2011)

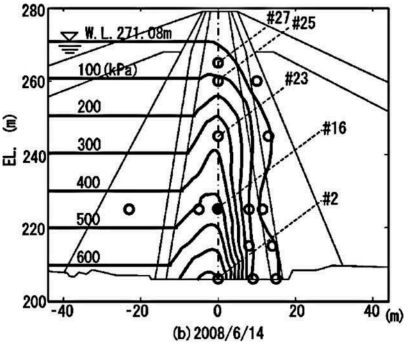

Figure 2. Pore pressure build-up recorded after the 2008 Miyagi earthquake (Ohmachi and Tahara, 2011)

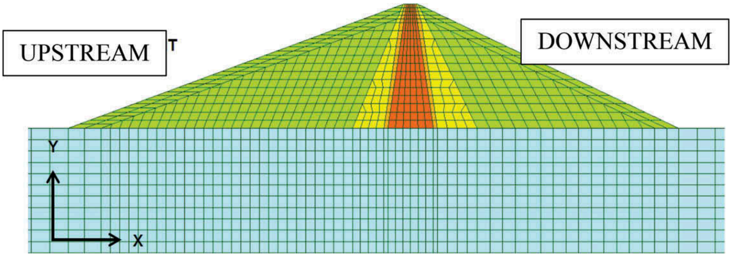

Figure 3. 2D mesh of Aratozawa dam

Absorbing boundary layers are placed around the foundation. The input signal consists of 2008 Miyagi horizontal accelerogram in the stream direction.

The main objective of this work is to verify the ability of the present model and associated calibration procedure to capture the behavior of the dam, and especially pore pressure build-up in the core. To this aim, 4 cases are considered:

- A fully mechanical model with Hujeux's model only, referred to as "Mechanical" model;
- A hydromechanical coupled model using pure water modulus K_w = 2GPa, referred to as "incompressible" model;
- A hydromechanical coupled model using Boutonnier's model for equivalent fluid modulus, referred to as "Boutonier H only" model;
- Finally, for the former and latter cases, a further calculation using both horizontal and vertical accelerograms is computed, referred to as "Mechanical H+V" and "Boutonier H+V" models.

3.3 CALIBRATION OF THE PHYSICAL MODELS FOR ARATOZAWA CORE MATERIAL

3.3.1 *Calibration of Hujeux's mechanical model*

Hujeux's constitutive model for soils requires calibrating 20 parameters. A calibration procedure was proposed by Lopez-Caballero (2007). Since the assessment of the core material compressibility is crucial for the prediction of pore pressure build-up, the main steps of a rational calibration based on common available geotechnical data and in the absence of laboratory tests, as it is the case here, are the following steps:

- Characterization of the position of the isotropic consolidation line (ICL) relative to the critical state line (CSL): knowing the liquidity limit w_L (≅57%) and assuming the compaction degree of the dam (95% for example), it is possible using appropriate correlations to derive the compressibility coefficient C_c and the position of the CSL, as explained by Lopez-Caballero (2007) and Boutonnier (2007, 2018). Knowing the undrained strength c_u, the ICL position can subsequently be derived;
- Characterization of the initial state by setting initial void ratio, pore pressure and effective confining stress. This can be done assuming a plausible initial water content (for example, $w = w_{OPN}+1$) and using appropriate correlations given by Boutonnier (2007, 2018);
- Characterization of cyclic softening. This is done by assuming a degradation curve for the shear modulus G. In Figure 4, the shear modulus degradation curve calibrated for Hujeux's model is compared to that given Oztoprak and Bolton for sands, Vucetic for clays and Ohmachi (2011) back-calculated curve for Aratozawa dam;

Any additional test data, if available, should be considered together with correlations proposed by Caballero and Boutonnier to better constrain the calibration of the model.

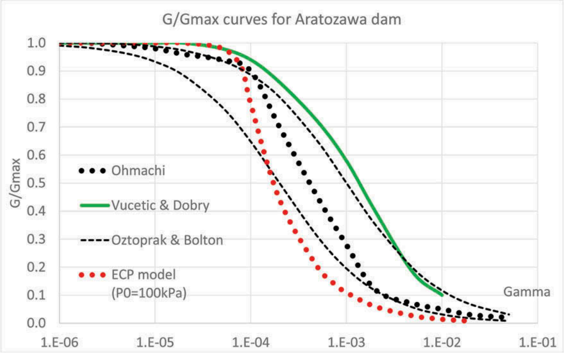

Figure 4. Comparison of the shear modulus degradation curve calculated for Hujeux's model and experimental curves given by Oztoprak and Bolton for sands, Vucetic for clays and Ohmachi for Aratozawa dam

3.3.2 *Calibration of Boutonnier's hydraulic model*

Following the procedure given by Boutonnier (2018), knowing the initial dry density and water content, the Proctor Optimum can be used to derive the residual saturation S_{re} (=0.96). The calibration result for the fluid equivalent modulus using Boutonnier's model for Aratozawa core is shown in Figure 5. It is observed that the presence of occluded air bubbles in water considerably decreases the modulus value compared to pure water (K_w = 2GPa), which may result in lower pore pressure build-up values.

3.4 *Results*

3.4.1 *Accelerations*

Comparison of horizontal accelerations calculated at crest with records is showed in Figure 6. It is observed that the de-amplification of the acceleration at crest is globally recovered in all cases (Table 1):

- The mechanical case with H only exhibits a PGA of 6.5 m/s^2, and that with H+V a PGA of 7.2 m/s^2. They also present higher acceleration amplitudes along the signal (Figure 6-a,b). This can be explained by a higher shear modulus than in the coupled case, where pore pressure build-up induced a confining stress drop and thus a drop of the shear modulus according to equation (1);
- The incompressible case exhibits the lowest PGA at 4.4 m/s2. The same explanation stands, i.e. a lower shear modulus induced by confining stress drop due to higher pore pressure build-up;

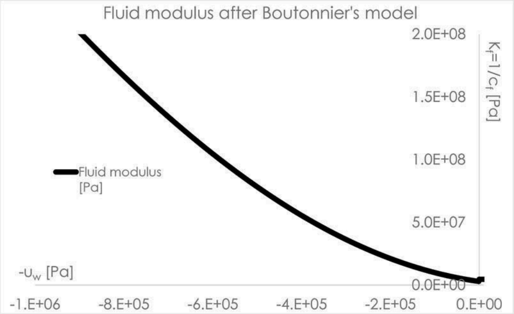

Figure 5. Calibration of fluid compressibility for Aratozwa core using Boutonier's model

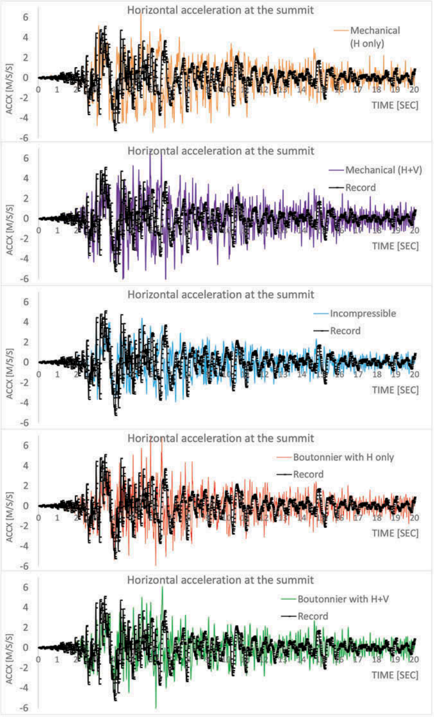

Figure 6. Comparion of horizontal accelerogramms computed at crest with record for the 5 cases

Table 1. Maximum horizontal acceleration computed at crest for the 4 cases

	Mechanical	Mechanical H+V	Incompressible	Boutonnier H	Boutonnier H+V
$a_{max}\ \left[m.s^{-2}\right]$	6.5	7.2	4.4	7	6

- Boutonnier's model with vertical component shows the best result with a PGA of 6 m/s^2, even better than that with horizontal component only with a PGA of 7 m/s^2;

For all cases, the transient results as well as the transfer functions (Figure 7) look quite satisfactory compared to the records, suggesting that as far as acceleration is concerned, a good

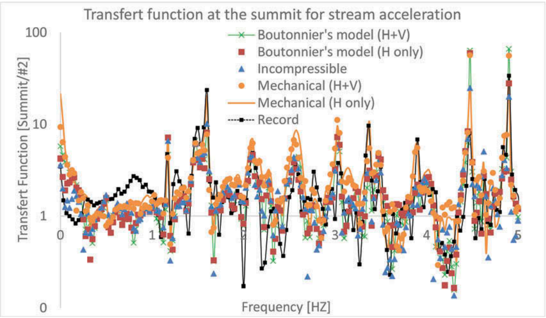

Figure 7. Comparion of transfer functions computed at crest with record for the 5 cases

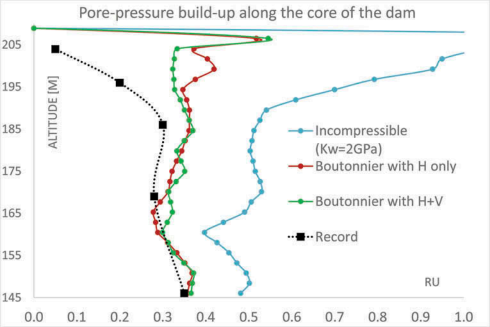

Figure 8. Comparison of computed pore-pressure build-up in terms of ru to record for the 3 coupled cases

calibration of G/G_{max} attenuation curves is sufficient to predict the experimental response. Furthermore, for both mechanical and coupled cases, the additional vertical acceleration shows little influence on the response.

3.4.2 *Pore pressure build-up*

Results for pore pressure build-up are compared to record in Figure 8 in terms of $r_u = \Delta u_w / \rho g z$ with $\rho = 2.09\ t.m^{-3}$. As expected, the incompressible case largely overestimates pore-pressure build-up in the core, whereas Boutonnier's model fits the record quite well at least on the two third bottom part of the core. However, on the one third top part of the core, all models overestimate the pore-pressure build-up. It is also observed that both cases with or without the vertical acceleration component exhibit quite close results. These results globally validate the rational procedure to calibrate the physical model.

3.4.3 *Settlement*

Finally, the settlement computed along the core is compared to the records in Figure 9. It is observed that all cases fail to predict the experimental settlement profile (settlement is concentrated on the top first 30m). More precisely for each case, it is observed that:

- The two mechanical models predict a settlement value at crest of about 40 cm, close to the recorded value. Vertical component of acceleration seems to have little influence on settlement;
- Boutonnier's model (with H only) and the incompressible model predict a settlement value at crest of about 60 cm, i.e. an overestimation by 50% of the recorded value;
- Finally, Boutonnier's model with vertical acceleration component gives the highest overprediction of settlement at crest with a value of about 70 cm. This is not surprising since it is expected that a more energetic input will produce higher non-linear effect;

These results may be interpreted as following:

- The coupled models induce a larger reduction of the dam rigidity by pore pressure build-up, leading to larger settlement than the mechanical case;
- Comparatively, water compressibility seems to have small influence on the settlement obtained just after the earthquake, even though they may have a larger influence on the final settlement after the dissipation of pore water pressure;
- Nonetheless, the settlement profile could not be correctly estimated, indicating that some failure mechanism is missing. In order to recover such a profile, Ohmachi et al. (2018) considered a sliding mechanism at the interface between the core and the filters at the top of the dam (Figure 10).

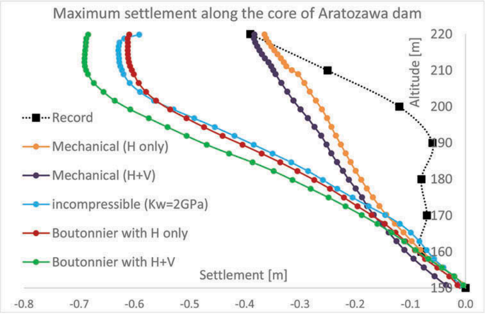

Figure 9. Comparison of computed settlement to record for the 5 cases

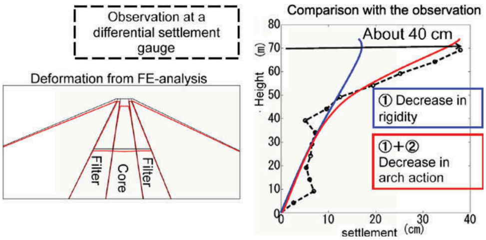

Figure 10. Sliding mechanism at the interface between the core and the filters suggested by Ohmachi and Tahara, 2018, to explain the settlement profile of Aratozawa dam

4 CONCLUSIONS

In his work, an advanced calculation methodology for the prediction of earthdams stability under earthquakes is presented. This methodology consists of a hydro-mechanical coupled method based on Hujeux's cyclic elastoplastic constitutive model for soils and on Boutonnier's model for pore fluid biphasic (water + air bubbles) phase. It is applied to the case of Aratozawa rockfill dam submitted to a strong shaking in 2008 for which a PGA up to 1g was recorded at the toe of the dam as well as the settlement and pore pressure build-up in the core. The dam response computed with the advanced model is compared to records, to a perfectly saturated case by incompressible water and to a perfectly drained case in terms of acceleration, pore water pressure build-up and settlement. It is concluded firstly that the purely drained slightly overestimates the PGA at crest compared to the coupled models. This can be explained by a larger drop of the shear modulus induced by pore water pressure build-up for the coupled cases than for the uncoupled one. Secondly, since the risk of liquefaction is to be assessed, the improved model taking occluded air into account leads to a better prediction of the pore pressure build-up in the core than using a perfectly saturated model. This goodness of fit is to be related to a simple methodology of calibration based on common field data. Thirdly, it is also observed that the coupled models overpredict the final settlement at crest compared to the perfectly drained model. However, the discrepancy of calculated and recorded settlement profile suggests that some failure mechanism is missing, as suggested by Ohmachi and Tahara, 2018.

REFERENCES

Boutonnier, L. 2018. Dynamic analysis of Aratozawa dam including the effect of occluded air and pore fluid compressibility. In ICOLD Proceedings. *Validation of Dynamic Analyses of Dams and Their Equipment*.

Lopez-Caballero, F. 2007. Nonlinear numerical method for earthquake site response analysis: 1) elasto-plastic cyclic model and parameter identification strategy. *Bulletin of Earthq. Eng.* 5: 303–323

Fry, J-J., Matsumoto, N. (2018) Validation of Dynamic Analyses of Dams and Their Equipment. *ICOLD Proceedings*

Ohmachi, T., Tahara, T. 2011. Nonlinear earthquake response characteristics of a central clay core rock-fill dam. *Soils and Foundations*, 51(2): 227–238

Ohmachi, T., Tahara, T. 2018. Analyses on earthquake-induced settlement of the Aratozawa dam due to the 2008 Iwate-Miyagi Nairiku earthquake. In ICOLD Proceedings. *Validation of Dynamic Analyses of Dams and Their Equipment*.