07. Seismic Hazard and Risk in Switzerland: From Science to Mitigation

Donat Fäh, Katrin Beyer, Blaise Duvernay

Schweizerische Gesellschaft für Erdbebeningenieurwesen und Baudynamik (SGEB)

TALKS:

7.1 Agalianos A., Sieber M., Anastasopoulos I.:: Simplified analysis method for bridges subjected to strike-slip faulting

7.2 Alber S., Anastasopoulos I.: On the development of a Bio-Inspired Self-Drilling Probe

7.3 Anastasopoulos I., Marin A., Sakellariadis L.: Optimized retrofit design of bridge pile groups


7.5 Bergamo P., Hammer C., Faeh D.: Progress in the compilation of multi-frequency seismic site amplification maps for the Earthquake Risk Model Switzerland project

7.6 Bodenmann L., ReuLand Y., Stojadinovic B.: Towards dynamically improving predictions of post-earthquake damage, loss and recovery for residential buildings

7.7 Božulić I., Vanin F., Beyer K.: Modelling of Strengthening in the Equivalent Element Approach


7.9 Glueer F., Häusler M., Gischig V., Fäh D.: Former ammunition depot Mitholz: seismic response of a rock mass damaged by accidental explosions

7.10 Hallo M., Bergamo P., Fäh D.: An approach to characterize high-frequency ground motion at depth

7.11 Häusler M., Glüer F., Fäh D.: Earthquake-induced mass movements in Switzerland: overview on past and ongoing projects

7.12 Imperatori W., Mai P.M., Faeh D.: SCARF3D: a scalable library to efficiently generate large-scale, three-dimensional random fields


7.15 Jones L., Anastasopoulos I.: Physical modelling of interaction between earthquake-induced Tsunamis and geotechnical structures

7.16 Kassas K., Adamidis O., Gerolymos N., Anastasopoulos I.: Seismic response of a structure on liquefiable soil

7.17 Khodaverdian A., Lestuzzi P.: A Scenario-based fragility model for Swiss buildings

7.18 Lontsi A.M., Shynkarenko A., Kremer K., Hobiger M., Bergamo P., Fabbri S., Fäh D.: A seismological survey on Lake Lucerne (Switzerland)
7.19 Marin A., Anastasopoulos I.: In-situ estimation of rocking stiffness of pile groups

7.20 Martakis P., Reuland P., Chatzi E.: Towards building-typology formulations that are adapted for structural health monitoring applications

7.21 Mizrahi L., Nandan S., Wiemer S.: The effect of declustering on the size distribution of mainshocks

7.22 Panzera F., Bergamo P., Fäh D.: Reconstruction of site amplification functions through canonical correlation with site proxies

7.23 Papadopoulos A., Roth P., Danciu L.: Exposure aggregation strategies for efficient assessment of seismic risk in Switzerland

7.24 Perron V., Bergamo P., Panzera F., Hammer C., Fäh D.: Empirical earthquake’s site response assessment in the Sion area, Switzerland


7.27 Rossi Y., Tatsis K., Arbogast K., Awadialjeed M., Chatzi E., Rothacher M., Clinton J.: Assessing a 6C Kalman filter using experimental datasets from an industrial robot

7.28 Sakellariadis L., Alig D., Anastasopoulos I.: Numerical study on the moment capacity of typical bridge pile groups on sand


7.30 Sieber M., Anastasopoulos I.: Simplified analysis for nonlinear foundation response


7.32 Weifeng Wu, Shiping Ge, Yong Yuan, Wenqi Ding, Anastasopoulos I.: Seismic Response of Underground Metro Station: Shake Table Testing and Numerical Simulation

POSTERS:


P 7.2 Lanza F., Diehl T., Herwegh M., Wiemer S.: Crustal Structure imaged by 3-D Seismic Attenuation for the Central Alps and their Foreland

P 7.3 Kremer K., Grolimund R., Fäh D.: Using the Swiss database of potential earthquake evidence to develop paleo-earthquake scenarios

7.1 Simplified analysis method for bridges subjected to strike-slip faulting

Athanasios Agalianos*, Max Sieber* & Ioannis Anastasopoulos*

*Institute for Geotechnical Engineering, ETH Zurich, Stefano-Francisci-Platz 5, CH-8093 Zurich (agaliana@ethz.ch)

Strike-slip faulting refers to fractures of the bedrock outcrop, where the predominantly horizontal tectonic movement takes place along the fault strike. During a seismic event, such fault ruptures propagate through the overlying soil layers, and may emerge at the ground surface, thus affecting the structures in their immediate vicinity. Focusing on bridges, several past case histories have demonstrated their vulnerability to such large tectonic deformations (e.g., Yang & Mavroeidis 2018). The bridge structural system significantly influences the deck distress, with statically indeterminate systems being vulnerable to the imposed deformation. On the contrary, statically determinate systems can accommodate differential displacements and rotations without significant distress, constituting a successful strategy for faulting-hazard mitigation (Anastasopoulos et al. 2008).

Aiming to bridge the existing gap in the literature, the present work examines the performance of a symmetric 3-span overpass bridge subjected to strike-slip faulting. The bridge is founded on shallow footings, resting on a 20 m deep dense sand layer. A detailed 3D Finite Element (FE) model of the entire bridge–foundation–abutment–soil system is developed in ABAQUS, accounting for both soil and superstructure nonlinearities (Figure 1). The soil behaviour is simulated with a thoroughly validated Mohr-Coulomb constitutive model with strain softening (Anastasopoulos et al. 2007), an essential feature to correctly simulate shear localization problems. Regarding nonlinear pier response, the concrete damaged plasticity (CDP) model of ABAQUS is implemented after thorough validation. The fault offset is applied in a quasi-static manner at the model base (representing the rock outcrop) in the transverse bridge direction. Its performance is parametrically analysed for various fault locations, accounting for the uncertainty with respect to its outcropping location.

The analyses confirm the susceptibility of the examined bridge structural system (continuous deck, monolithic pier-deck connections) to fault-induced differential settlements, which lead to axial load redistribution between the 2 piers and the abutments. Moreover, due to the monolithic pier-deck connections and the deck continuity, both the bridge deck and the piers are subjected during faulting to significant biaxial bending, shear and torsion. The system response highly depends on the exact fault outcrop location, emphasizing the need to develop simplified analysis techniques to perform series of parametric analyses.

Such a simplified analysis technique is described herein, including detailed modelling of the superstructure, similarly to the detailed model, while the soil-foundation system is modelled rigorously only for the pier directly affected by the fault. The soil-foundation interaction of the remaining piers is considered through properly calibrated nonlinear springs (Figure 2a). The proposed simplified method compares quite well to the detailed analyses, as indicatively depicted in Figure 2b in terms of deck out-of-plane bending moment \( M_z \) for fault offset \( h = 2 \) m underneath pier P1. Its main limitation, leading to the observed discrepancies, is identified as its inability to account for the fault-induced axial load redistribution by employing nonlinear springs. Overall, it constitutes a computationally efficient means to parametrically analyse long multi-span bridges subjected to strike-slip faulting for design purposes.
Figure 2. (a) Schematic illustration of the proposed simplified analysis technique and (b) example comparison between detailed and simplified analysis for fault offset \( h = 2 \text{ m} \) underneath pier P1 in terms of deck bending moment \( M_z \).

REFERENCES


On the development of a Bio-Inspired Self-Drilling Probe

Simone Alber*, Ioannis Anastasopoulos*

*Institute for Geotechnical Engineering, ETH Zürich, Stefano-Franscini-Platz 5, CH-8093 Zürich
(simone.alber@igt.baug.ethz.ch)

The seismic design of new and the retrofit of existing structures call for careful site investigation for the acquisition of soil properties. Especially in the case of seismic retrofit of existing structures, project sites are not easily accessible for conventional drill or penetration rigs, rendering soil investigation difficult (if not impossible) in close proximity to the examined structure. Efforts are dedicated to the development of an advanced, self-drilling probe for in-situ soil assessment, which will be able to perform an autonomous subsurface movement without the necessity of the reaction force by drilling rigs. Self-driven probes that are designed for planetary exploration to access subsurface sites on Mars or Moon are often based on the underground locomotion mechanisms found in nature (e.g. Nagaoka et al. 2010; Omori et al. 2013). The self-drilling probe described herein is bio-inspired, following the locomotion mechanism of inchworms. Figure 1 illustrates the subsurface inchworm locomotion sequence of the self-drilling probe.

The device includes forward and rearward anchors for the generation of reaction force on the borehole wall, which allows the propulsion unit of the device to push forward the front or rear part. The self-drilling probe is excavating at the front through a rotating cutting edge, which is connected to a central tube and conveys the excavated soil through the probe to the back by means of a discharging mechanism using an auger. After advancement, the forward anchors are expanded to secure the device to the borehole wall and the rearward anchors are retracted, as well as the propulsion unit, to pull the rear end of the device towards the front. Because of its ability to advance in the soil and simultaneously excavate material without the generation of lateral pressure or rotation at the frontal bit, the device offers minimal soil disturbance at the front and therefore undisturbed soil conditions. The frontal bit can be considered as a measurement "cell", where pressuremeter testing or shear-wave velocity measurements with bender elements can be conducted under "undisturbed" conditions. After this step, the device goes back in the original position. The prototype of the propulsion unit during advancement in a Plexiglas tube is shown in Figure 2. The anchoring system is currently in the construction phase and the front unit with the excavating bit and the measuring part are in the design phase. Especially the conception of the excavating unit is challenging, as gravelly material or dense soil are most likely to pose a challenge in producing a self-drilling probe with its own insertion reaction (Khosravi et al. 2018). However, the generation of sufficient reaction force in-situ within the device offers a decisive advantage over conventional instruments. The autonomous advancement of the self-drilling probe can yield valuable information of in-situ soil parameters close to the future or existing structure of interest or even below it, while avoiding empiricism. This allows for more accuracy and reliability in the design of geotechnical structures.

Figure 1. Penetration sequence of the underground self-drilling probe.

Figure 2. Prototype of the propulsion unit during advancement in a Plexiglas tube.
Figure 2. Prototype of the propulsion unit in a Plexiglas tube (Simone Alber).

REFERENCES
7.3 Optimized retrofit design of bridge pile groups

Ioannis Anastasopoulos*, Alexandru Marin*, Lampros Sakellariadis*

*Institute for Geotechnical Engineering, ETH Zurich, Stefano-Francini-Platz 5, CH-8093 Zürich (ixa@ethz.ch)

Pile groups are often over-designed due to excessive conservatism of current design practice, which tends to underestimate vertical bearing capacity of single piles. Such inaccuracies lead to substantial underestimations of moment capacity of pile groups. Consequently, road and rail infrastructure projects are associated with unjustified increased costs and construction time, and low levels of sustainability. The ASTRA project AGB2017/001, funded by the Federal Road Office (FEDRO), proposes three main directions of research in the attempt to deal with the above mentioned design issues.

Firstly, the possibility of introducing concepts of ductility in geotechnical design (Anastasopoulos et al., 2010) is explored, with the aim of reducing excessive levels of conservatism and rationalizing design practice. The full moment capacity of pile groups can be utilized and the design conservatism can be decreased by allowing progressive full mobilization of vertical pile bearing capacity and load redistribution from the edge towards the inner rows of piles. Preliminary numerical investigations (Fig. 1) indicate that the resulting increased moment capacity obtained by implementing such concepts in engineering practice can exceed by up to 400% the values suggested by current design codes. Moreover, a ductile energy dissipation mechanism develops through progressive bearing capacity mobilization during earthquakes and the seismic performance of pile groups improves at the cost of residual deformations that can be accounted for in design.

Secondly, existing methods for the estimation of the bearing capacity of piles are refined for more accurate results. Only in this way, ductile geotechnical design concepts can be implemented. Available data (e.g., CPT, pile-load tests) is used in conjunction with centrifuge tests and numerical analyses (Fig. 2), aiming to understand the concepts behind correlations of in-situ tests and corresponding bearing capacity estimates of piles. Moreover, most appropriate in-situ investigations and correlations are identified based on their capability to produce accurate estimates of vertical bearing capacity of single piles.

Last but not least, an innovative technique for the measurement of the rocking stiffness of existing pile groups is developed (Fig. 3). A low-amplitude non-destructive testing method is envisaged, with a dynamic load applied at the top of the bridge pier. The vibration response (i.e., lateral drift of pier and rotations of pile cap) is measured, and the stiffness parameters of the pier and pile group estimated.
Figure 3. In-situ measurement technique for the estimation of stiffness parameters of bridge piers and pile groups.

The possibility of correlating the real stiffness with the actual moment capacity of pile groups is explored numerically and experimentally. To this end, simplified models based on beam-and-springs assemblies able to capture the monotonic lateral response of bridge piers and their foundations are developed. Parametric analyses can be performed and useful correlations can be developed with the help of such models.

REFERENCES

AIT, 2020: Mobile seismic simulator. Austrian Institute of Technology - Center for Mobility Systems, Vienna, Austria.
Following the ambitious energy targets set by countries worldwide, the offshore wind sector has seen impressive growth over the past decade, transforming from niche technology to a global industry. The vast spread of offshore wind turbine (OWT) installations has apparently broadened the hazardous sources that threaten this kind of infrastructure (Katsanos et al., 2016). In recent years, an extensive number of wind turbines has been or is planned to be installed in high-seismicity areas, such as China, Taiwan, India and South Korea, as well as in the USA, Mexico and several seismic active zones of Southern Europe, thus raising demanding concerns on the structural robustness of OWTs against a seismic environment.

At the same time, the industry’s favorite monopile becomes financially inefficient for transitional water depths of 30 – 60m, while the offshore construction industry struggles to comply with the strict federal policies of limiting noise emissions during pile driving. On the other hand, jacket structures are gaining ground, with the industry making substantial progress towards standardized manufacturing and mass production of tubular joints using automatic welding procedures. Although hardly a new concept, jackets are gradually establishing their position in the offshore market (Wagner et al., 2011), being at the moment the second most installed OWT foundation in Europe (WindEurope, 2020).

Since 2018, suction caissons have been commercially deployed to support jacket structures in intermediate water depths, with installations taking place at the Borkum Riffgrund 1 (2014; one position), Borkum Riffgrund 2 (2018; 20 positions) and Aberdeen Bay (2018; 11 positions) offshore windfarms. Operating as the foundation system of jacket OWTs, suction caissons are primarily called to withstand vertical loading; the jacket structure assumes the environmental actions through rigid frame action, which is subsequently translated at the foundation level as a pair of axial forces. Despite the rise of this foundation solution within the offshore market, investigations of the dynamic axial response of Suction Bucket Jackets (SBJs) has received much less attention in the recent literature (e.g., Skau et al., 2018).

Motivated by the recent advancements in the use of SBJs for the support of OWTs, this study applies a rigorous FE analysis methodology to study their response under concurrent wind and seismic loading, proposing a novel intensity-measures-based methodology for performance-based seismic assessment of SBJs founded in clay. A dimensional analysis of axially-loaded suction caissons in clay is used as a means of generalizing the results of an extensive numerical analyses campaign, where the performance of SBJs in terms of caisson residual settlements is critically assessed against a number of selected Intensity Measures (IMs). In an effort to reduce variability in performance and guide design decisions, the study concludes on a unique correlation of permanent caisson settlement with a single IM, the Arias Intensity, and presents results in the form of easy-to-use caisson settlement charts (Fig.1.). The latter may serve as a simplified method to estimate foundation settlement under various seismic design load combinations, without the need to analyze the entire soil-foundation-structure-interaction problem.

REFERENCES
Figure 1. Example correlation of dimensionless caisson settlement ($w/D$) with Arias Intensity ($IA$), for different values of soil rigidity ratio ($E/S_u$) and vertical capacity ratio ($V/S_o D^2$).
7.5 Progress in the compilation of multi-frequency seismic site amplification maps for the Earthquake Risk Model Switzerland project

Paolo Bergamo*, Conny Hammer*, & Donat Fäh*

*Swiss Seismological Service (SED) at ETH Zürich, Sonneggstrasse 5, CH-8092 Zürich (paolo.bergamo@sed.ethz.ch)

The site response module of the Earthquake Risk Model Switzerland project articulates its development at three scales of investigation: national, regional and local scale. At each level, the final target is producing a layer representing the spatial variability of the site amplification term of ground motion, originating from the seismic response of the local geology. As for the national scale, the intended final product is a set of frequency-dependent amplification maps covering the Swiss territory. The strategy devised for this purpose involves resorting to the empirical amplification functions obtained with the spectral modeling technique (Edwards et al., 2013) at all free-field seismic stations (~250) of the Swiss networks. These empirical amplification functions are then to be "spread" with the help of auxiliary variables (site condition indicators, such as parameters derived from DEM or geological thematic maps; or geophysical measurements, such as H/V noise surveys, available at more than 6000 locations). The preferred extrapolation method was identified as the neural network (NN) technique (Bergamo et al. 2019a). However, numerous tests performed in the framework of the project (Bergamo et al., 2019b) have evidenced that i) the Swiss database of amplification and site condition information is not large enough to robustly constrain the NN parameters, and ii) that it is not possible to integrate the Swiss dataset with data from other regions (e.g. Japan), as far as indirect site condition indicators (topographical, geological parameters) are concerned. Therefore, we have been forced to explore the possibility to replace the NN with a Bayesian Network (BN), able to handle smaller and/or partly incomplete training datasets. While waiting for the first results from the BN, we have prepared a set of provisional site amplification maps where the local amplification is extrapolated by means of regressions on three support variables, identified as the most significant:

1. Coarse lithological classification of the Swiss territory, based on the 1:500000 geological map of Switzerland (Figure 1, top). The classification was cross-referenced with ~225 velocity profiles from the SED site characterization database (http://stations.seismo.ethz.ch) to ensure its significance in terms of geophysical properties;
2. Topographical slope. The amplification factors at each frequency ordinate were correlated with the slope evaluated at the spatial scale for which the correlation is maximized: 525 m for 0.5 – 1 Hz (Figure 1, bottom right), 225 m for 2.5 – 3.33 Hz, 125 m for 4 Hz, 75 m for 5 Hz;
3. Map of the depth of the quaternary sediments-bedrock horizon (Swisstopo, 2019). This model was collated with ~225 velocity profiles from the SED site characterization database, evidencing a fair agreement between the two datasets for depths > 5 m.

We produced 7 maps for as many frequency ordinates in the range 0.5 – 5 Hz, and additionally a PGV amplification map (Figure 1, bottom left); these maps are to be integrated in the first global test of the Risk Model project. The reliability of the produced maps was positively tested with a comparison between predicted and empirically-measured amplification at 11 recently installed stations not included in the training dataset. Next steps in our work include, in the short term, a further refinement of the maps by forcing the predicted amplification at and around instrumented sites to comply with the measured one, with a regression-kriging algorithm. In the medium term, we intend to pursue the Bayesian network strategy that will allegedly offer a more flexible tool for the correlation between site condition information and amplification.

REFERENCES
Federal Office for Topography (Swisstopo), 2019. Thickness model of unconsolidated deposits.
Figure 1. Top: map of the adopted geological classification for Switzerland and locations of the seismic stations. Bottom left: produced amplification map at 1 Hz. Bottom right: example of correlation between slope (525 m scale) and amplification factors (at 1 Hz) from the stations deployed on ‘gravel and sand, with clay or silt’ formations.
Towards dynamically improving predictions of post-earthquake damage, loss and recovery for residential buildings

Lukas Bodenmann*, Yves Reuland*, Božidar Stojadinović*

*Dept. of Civil, Environmental and Geomatic Engineering, ETH Zurich, Stefano-Franscini-Platz 5, CH-8093 Zürich (bodenmann@ibk.baug.ethz.ch)

Earthquake disasters manifest in widespread damage to the built environment. This damage induces numerous direct and indirect consequences that often plague the affected communities long after an earthquake. Damage limitation via adequate design of new buildings and strengthening of existing buildings is one crucial pillar in earthquake risk mitigation. Because only small fractions of the existing building stock are renewed every year and because modern, code-conforming buildings may also suffer damage in rare events, planning and practicing disaster response and recovery actions is key to reducing negative impacts from earthquake-damaged buildings on the stricken community. However, an ex-ante development of optimal strategies for every possible scenario is not feasible. Instead, public and private stakeholders will have to shape the recovery path ex-post, in a decision environment characterized by high stakes and time pressure using scarce and uncertain data on the consequences inflicted by the event. For example, rapid safety screenings of all affected buildings might take from a few days to several weeks, depending on the severity of the event, the available engineering inspection resources and the accessibility of the affected region.

Hence, consequence models play a crucial role in offering first rapid impact predictions to decision-makers and the general public in the immediate aftermath of an earthquake event. However, the uncertainties inherent to every step of such models (such as shaking characteristics, building response, fragility of components, cost and duration of repairs) lead to wide ranges of possible outcomes. On the other hand the amount and the spatial coverage of event-specific consequence data increases during the response and recovery processes. This includes, amongst others, information from completed visual safety screenings, measurement-based structural health monitoring and post-processed aerial imageries. To provide stakeholders with up-to-date information for their post-earthquake decision-making, a framework is developed that continuously integrates and combines event-specific data, gathered ex-post, with consequence models, developed ex-ante. The transparent propagation of uncertainties present in the models and the data, enables dynamic updates and refinements of post-earthquake predictions on the spatial distribution of damage, loss and recovery.

A preliminary version of this dynamic framework is demonstrated using a small-scale simulated case study focused on residential buildings, which allows to discuss key aspects of ex-post data availability and to compare the proposed framework with existing methods for similar purposes (e.g., Loos et al. 2020; Kovačević et al. 2018, Marinković et al. 2018). A successful tailoring of such a framework to Switzerland requires not only discussions on the type and resolution of the desired information gathering, processing and output, but also on data availability and quality, planned procedures for rapid safety screenings and recovery (Gunzenhauser et al. 2018), as well as on the type and scope of models developed within the Swiss national earthquake risk model (Roth et al. 2018).

REFERENCES

7.7 Modelling of Strengthening in the Equivalent Element Approach

Ivana Božulić*, Francesco Vanin*, Katrin Beyer*

*Laboratory of Earthquake Engineering and Structural Dynamics (EESD), School of Architecture, Civil and Environmental Engineering (ENAC), Ecole Polytechnique Fédérale de Lausanne (EPFL), EPFL ENAC IIC EESD, GC B2 495, Station 18, CH-1015 Lausanne, Switzerland (katrin.beyer@epfl.ch)

The seismic vulnerability of existing masonry buildings can be reduced by applying various strengthening solutions. A recently developed 3D macroelement for modeling both in-plane and out-of-plane response allows analyzing masonry buildings in a computational efficient manner considering all relevant failure modes. The objective of this paper is to investigate the use of this macroelement for modeling the effect of FRP strengthening on the in-plane and out-of-plane response of masonry walls.

The increase in flexural in-plane and out-of-plane strength due to FRP strengthening is accounted for by defining the flexural capacity through a fibre section, which includes the vertical FRP strips. The effect of the FRP strengthening on shear strength and deformation capacity is modifying the corresponding parameters in the phenomenological macroelement equations. In this paper, in-plane monotonic and cyclic shear-compression tests, in-plane dynamic test, as well as four-point out-of-plane bending tests with and without FRP strengthening, which are documented in the literature, are modelled and the numerical simulations compared to the experimental results.

The comparisons show that the proposed modelling approach for FRP strengthened masonry walls yields good predictions of their in-plane and out-of-plane response. Equivalent frame models can therefore be used to model the system response of masonry buildings with FRP strengthened walls.

7.8 Testing of additively manufactured small scale RC specimens for statistical validation of structural models in earthquake engineering

Lorenzo Del Giudice1, Rafal Wrobel2, Christian Leinenbach2, and Michalis F. Vassiliou1

1 IBK, ETH Zurich Stefano-Franscini-Platz 5, CH-8093 Zurich
e-mail: {delgiudice, vassiliou}@ibk.baug.ethz.ch
2 Empa, Swiss Laboratories for Materials Science and Technology Überlandstrasse 129, CH-8600 Dübendorf
{rafal.wrobel, christian.leinenbach}@empa.ch

This paper claims that a major source of error in Seismic Analysis of Structures is the assumptions used to scale up from component- to system-level behavior. It also claims that validation of numerical models should be performed statistically. As a statistical validation requires multiple virgin specimens, the paper suggests the use of a 3D printer to construct the reinforcement of microRC specimens (1:40) to be tested in a geotechnical centrifuge. It presents some first tests on gypsum-based microconcrete, additively manufactured rebars with diameters as low as 0.35mm, and small scale RC beams. The properties observed seem to resemble the ones of full scale RC components. Given the material properties, OpenSees is able to accurately capture the behavior of the microbeam.
7.9
Former ammunition depot Mitholz: seismic response of a rock mass damaged by accidental explosions

Franziska Glueer*, Mauro Häusler*, Valentin Gischig**, Donat Fäh *

*Swiss Seismological Service (SED), ETH Zurich, Sonneggstr. 5, CH-8092 Zurich (franziska.glueer@sed.ethz.ch)
** CSD Ingenieure AG, Hessstrasse 27d, CH-3097 Liebefeld

In 1947, an uncontrolled explosion of the subsurface ammunition storage Mitholz in the Swiss Kander Valley caused several fatalities, the partly destruction of the ammunition storage and the adjacent village of Mitholz – and a leftover of 3'500 t of unrecovered ammunition remnants. In 2018, a risk analysis of the site, which until then was used for military purposes and was planned to host a computer server centre, revealed unacceptable risks for the surroundings of the depot.

Especially rock falls and earthquake-induced ignition of the ammunition were considered high (10^{-3} to 10^{-2} per year, estimated by Risk&Safety AG (2018)). In the course of a more detailed investigation on seismic stability (a.o. with CSD Ingenieure AG) ambient vibration measurements at Mitholz were performed to support the further assessment of the rock characteristics. A combination of the field measurements with numerical simulations aimed to understand the seismic stability of the damaged cavern.

For an array measurement 21 seismic sensors (LE-3D 5-s and LE-3Dlite 1-s) were located both inside the tunnel system and outside at the surface above the cavern (Figure 1). The seismic response was analyzed with all state-of-the-art methods (amplification, polarization and normal mode behaviour) as described e.g. in Burjanek et al. (2014), Kleinbrod et al. (2019) and Häusler et al. (2019). Amplification factors are highest in the area just above the destroyed cavern and fracturing of the rock mass decreases the further away stations were located from the centre of the detonation (Figure 1c). Polarization direction is east-west – in line with the predominant geological fracturing and faulting of the underlying early creataceous limestone (Oehrlikalk).

Results of these measurements were used to calibrate the elastic properties of a 2D model to analyze the earthquake stability of the underground structure. Earthquake-induced displacement patterns of the rockmass involve rockfall of instable blocks at the outside (Dreispitz), rockfall and breakdowns within the caverns, and even a complete collapse of the tunnel system along the pre-existing fault-system of the Mitholz-fault seems possible. This study shows, that ambient vibration measurements and their analysis can be succesfully applied to characterize the subsurface not only for mass movements, but also to special cases of superficial mass displacements like underground explosions.

REFERENCES
Figure 1. Location of the 1947 detonated underground ammunition storage chamber at Mitholz and results of the ambient vibration measurements. a) Measuring configuration of the passive seismic array at the Drüspitz peaks and the plateau Uf der Flue; b) Location of the site in Switzerland between Kandersteg and Kandergroden and the topography and naming of the area; c) Amplification map of the mode shape at 3 Hz with the arrows indicating the normal mode vector (polarization).
7.10

An approach to characterize high-frequency ground motion at depth

Miroslav Hallo*, Paolo Bergamo*, Donat Fäh*

*Schweizerischer Erdbebendienst (SED), ETH Zürich, Sonneggstrasse 5, CH-8092 Zürich (miroslav.hallo@sed.ethz.ch)

The site-specific high-frequency (>1Hz) attenuation and amplification are essential for the prediction of the ground-motions on a local scale. Amplification is generally modeled using Vs30 adjustments on classical ground-motion prediction equations while attenuation is usually concisely described with parameter kappa; however, these approximations are subject to high epistemic uncertainties. Furthermore, there is a need to characterize ground motion at depth in the seismic hazard assessment of deep geological disposals (e.g. nuclear waste repositories), with a particular need to characterize high-frequency ground motion for seismic design purpose.

In this research, we aim to develop a physical-based approach to construct stochastic depth-to-surface amplification models. We first derive a set of 1D velocity profiles based on geophysical measurements and considering various possible random effects of the near-surface geology on ground motions. These random models are then used for computation of an ensemble of the depth-to-surface SH-wave transfer functions. The ensemble of such transfer functions is used for the construction of the stochastic model shown in Fig. 1 through statistics in the power spectral density (amplification term) and the envelope delay (temporal term). Finally, we compare theoretical predictions with empirical depth-to-surface amplifications and durations as retrieved from borehole installations of the Japanese KIK-net network.

Our approach has many various applications, such as: the inversion on the high-frequency ground motion at depth from surface recordings, the site-specific stochastic adjustments on classical ground-motion prediction equations, the evaluation of the systematic bias in the representation of the local site response intrinsic to downhole seismometer arrays (e.g. interaction of up- and down-going waves, etc.

![Figure 1](https://example.com/figure1.png)

Figure 1. The model to characterize the ground motion at depth with respect to the surface. The model represents statistical properties from an ensemble of depth-to-surface SH-wave transfer functions in randomly perturbed velocity models.
Earthquake-induced mass movements in Switzerland: overview on past and ongoing projects

Mauro Häusler*, Franziska Glüer*, Donat Fäh*

*Swiss Seismological Service, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich
(mauro.haeusler@sed.ethz.ch)

Earthquake-induced landslides and rockfalls are common during and after seismic events with ~PGA 0.18 g (EMS macroseismic intensity VI to VII) and larger. In the Swiss Alps, the probability of such an intensity generally exceeds 10% in 50 years and reaches values up to 75% in southwestern Switzerland (Wiemer et al., 2016). Testimonials of earthquake-induced landslides are the destruction of the villages Corbeyrier and Yvornaz following the Mw 5.9 Aigle earthquake in 1584, the rockfall from Bürgenstock during the Mw 5.9 event 1601 in Unterwalden, and the 5 million m$^3$ rock avalanche at Rawilhorn during the largest aftershock of the 1946 Mw 5.8 Sierre earthquake (Figure 1).

Detailed studies on seismic site response of unstable slopes in Switzerland started with the COGEAR (Coupled Seismogenic Geohazards in Alpine Regions) project in 2009 (Fäh et al., 2012). Key findings include the observation of high seismic amplification factors (>7) and wavefield directivity perpendicular to compliant fractures (e.g. Burjánek et al., 2012). Geospatial susceptibility proxies, such as topography, and ground motion prediction models allow for estimating the probability of coseismic landslides on a regional scale (Cauzzi et al., 2018). However, extensive field experiments on more than 25 slope instabilities in Switzerland revealed a great variety in dynamic response, including wavefield amplification factors larger than 35, normal mode resonance behavior and slopes exhibiting surface wave propagation (Kleinbrod et al., 2019). Therefore, site-specific analysis of a slope remains crucial to assess the hazard of coseismic mass movements on a particular location.

We present an overview on past and ongoing projects in the field of earthquake-induced mass movements in Switzerland and demonstrate how the methodology, which was developed to assess seismic site response, can be applied in environmental seismology to characterize rock slope instabilities in general, independent of potential triggering by earthquakes.

Figure 1. Deposits of the earthquake-induced rock avalanche at Rawilhorn (Valais) after an aftershock of the 1946 Mw 5.8 earthquake. Copyright: ETH-Bibliothek Zürich, Bildarchiv / Fotograf: Wehrli, Leo / Dia_247-14750 / CC BY-SA 4.0
REFERENCES
7.12
SCARF3D: a scalable library to efficiently generate large-scale, three-dimensional random fields

Walter Imperatori*, Martin P. Mai**, Donat Fäh*

*Swiss Seismological Service, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich (walter.imperatori@sed.ethz.ch)
**King Abdullah University of Science and Technology, Thuwal 23955, KSA

Numerical modelling of strong ground motion requires realistic structural models that allow simulation of all wave propagation phenomena. One dominant process is wave scattering due to small heterogeneities, associated to strong effects in terms of ground motion attenuation and duration. Starting point are realistic 3D models derived from extensive geological and geophysical field investigation. However, small scale changes in properties of geologic units can be characterized only by random variations. We present a new numerical package to efficiently generate large-scale, three-dimensional random fields with prescribed power spectrum. Our software can be used either as a stand-alone program or as a library and it can be therefore invoked by other computer programs to generate random perturbations directly on the nodes of structured and unstructured meshes, thus avoiding costly intermediate input-output operations. The code is highly flexible and allows the user to easily generate continuous multi-resolution random fields across mesh refinement interfaces. It implements two different algorithms that can be selected depending on the available hardware resources. The package relies on the popular MPI and FFTW libraries and it has been tested from desktop machines up to hybrid CPU/GPU supercomputers, showing very good scaling properties. The simulated random fields closely follow the desired autocorrelation function.
7.13
Developing an Integrated 3D Geological-Seismological Model at Urban Scale in Basel, Switzerland

Afifa Imtiaz*, Francesco Panzera*, Horst Dresmann**, Brian Steiner**, Donat Fäh

* Swiss Seismological Service (SED), ETHZ, Switzerland (afifa.imtiaz@sed.ethz.ch)
** Applied and Environmental Geology (AUG), University of Basel, Switzerland

Assessment of seismic risk at a local scale is fundamental to the adoption of efficient risk mitigation strategies for urban areas with spatially distributed building portfolios and infrastructure systems. An important component of such a study is to estimate the spatial distribution of the expected seismic ground motion induced by site response.

The current work presents a prototype of seismic site response study at urban scale, performed in the context of developing an earthquake risk model for the canton of Basel-City in Switzerland. Different studies undertaken over last two decades in the area concluded that unconsolidated sediments were responsible for inducing fundamental resonance and large amplification of seismic waves over a range of frequencies pertinent to engineering interest. They also highlighted the necessity of better characterizing complex geological domains (the Upper Rhine Graben and the Tabular Jura) and tectonic setting (the master-fault system of the Graben) of the area. Therefore, we make a step forward in this study by attempting to develop a three-dimensional (3D) integrated geological-seismological model of Basel, which will explicitly account for the complex geological conditions at the surface and at depth.

Thanks to the past projects (see Michel & Fäh 2016 for a review), there is an abundance of geological, geophysical and seismological data for Basel. Earthquake recordings are available from an operating network of more than 20 permanent stations as well as from several former temporary stations. Single station ambient noise measurements are available from several hundred sites. Shear-wave velocity profiles have been obtained from more than 25 passive seismic arrays. In addition, a number of active seismic measurements and borehole logs are also available. This database will be complemented by 6 additional temporary stations (2020-2023) along with new passive seismic measurements. An updated and detailed 3D model of subsurface geological structure of the area has been provided by the team of Applied and Environmental Geology (AUG) of University of Basel.

The ongoing analysis of the available information will (1) better identify the composition, geometry, thickness and topography of the surficial unconsolidated sediments as well as the underlying more consolidated layers, and (2) characterize them by means of geophysical parameters (e.g. resonance frequency, shear-wave velocity). The results will then be compiled into the aforementioned 3D model. Ground motion simulation and 1D site response study will be performed in order to validate the developed model with respect to seismic observations. This model will be used to simulate 3D amplification effects and risk scenarios for Basel city.

REFERENCES
Figure 1. Locations of available geophysical and seismological data for Basel. A high resolution (HR) 3D geological-seismological model will be developed for the area bounded by the red polygon.
Evaluation of the variability of soil response in urban environment using reference-site methods: the case of Lucerne, Switzerland

Paulina Janusz*, Vincent Perron*, Christoph Knellwolf**, Walter Imperatori*, Luis Fabian Bonilla*** & Donat Fäh*

* Swiss Seismological Service, ETH Zürich, Sonneggstrasse 5, 8092 Zürich, Switzerland (paulina.janusz@sed.ethz.ch)
** Verkehr und Infrastruktur, Abteilung Naturgefahren, Kanton Luzern, Arsenalstrasse 43, 6010 Kriens, Switzerland
*** Université Gustave Eiffel, 14-20 Boulevard Newton, Cité Descartes, 77447 Marne-la-Vallée Cedex 2, France

The long-term seismic risk cannot be neglected even in low-to-moderate seismicity countries like Switzerland, especially in densely populated urban areas. Site effects evaluation is a crucial part of local seismic hazard and risk assessment. The focus of this study is the city of Lucerne, located in a basin filled with unconsolidated deposits and struck by strong earthquakes in the past (i.e. Mw 5.9 in 1601). Our aim is the estimation of the site response in different parts of the city and a better characterization of the influence and variability of the local geological structure. This work is in the framework of the European URBASIS project concentrated on seismic hazard and risk in urban areas.

In the presented analysis, we used the weak motion observations from low-magnitude or distant earthquakes recorded by a temporary seismic network installed for half a year at selected urban sites. The dataset was supplemented by earthquake recordings at 3 permanent accelerometric stations belonging to the Swiss Strong Motion Network (SSMNet). We show the comparison of relative amplification factors evaluated using standard spectral ratio method applied to earthquakes (SSR - Borcherdt, 1970) and ambient noise (SSRn – Kagami, 1982) recordings, as well as a hybrid approach (SSRh) combining these two techniques (Perron et al., 2018). While amplification estimated with SSRn is usually overestimated in comparison to the SSR, matching results were obtained using the SSRh method. Another presented approach based on regional earthquake recordings is Empirical Spectral Modelling (ESM - Edwards et al., 2013). ESM shows consistent results with the SSR method due to similarities between the outcropping rock in Lucerne with the Swiss reference rock used in ESM.

In the next step, we applied the SSRh technique to estimate the spatial variability of basin response in a test area. A survey including several dozens densely distributed single-station noise measurements was performed in June 2020. Moreover, we combined our dataset and recordings from the past 20 years in the Lucerne city center to map the fundamental resonance frequency (f0) across the area.

This work represents the first step in a detailed site response analysis study for the Lucerne area, considering 2D and 3D effects and potential non-linear soil behaviour as well. We present the current status of the ongoing site effects assessment, highlighting the limitations and specifics of the site characterization in urban areas.

REFERENCES


Figure 1. Amplification factors with respect to the rock station HOR01 estimated using the SSRh method. Blue triangles represent sites where earthquake recordings are available, black circles are ambient noise measurements.
Physical modelling of interaction between earthquake-induced Tsunamis and geotechnical structures

Liam Jones*, Ioannis Anastasopoulos*

*Chair of Geotechnical Engineering, ETH Zürich, Stephano-Franscini-Platz 5, CH-8093 Zürich
(liam.jones@igt.baug.ethz.ch)

Catastrophic hydrodynamic events, such as earthquake-induced Tsunamis can devastate society and the built environment. A good deal of this destruction is a result of a combination of scouring, the loss of support material, and hydraulic loading (Bricker et al., 2015). Modelling such systems numerically is generally beyond our current abilities for all but the most simplistic scenarios and the difficulty in predicting the behaviour of these structures under these loads makes designing new structures, or assessing old ones, extremely difficult.

To bridge this gap, the problem is investigated through physical modelling, with particular emphasis on the complex geotechnical aspects of the problem which are often neglected in hydraulic models. Using scaled models, with an innovative “Miniaturised Tidal Generator” (Fig. 1) in combination with advanced non-intrusive sensing techniques, we are able to see subtle (but critical) changes in soil systems throughout the scour process. These include both complex changes in system geometry and changes in soil state. Such observations are critical to guiding the research, and ultimately design of coastal or near-water infrastructure.

Figure 1. Schematic function of the “Tidal Generator” System, where air pressure is used to generate large length and amplitude waves.

The model is a 1:100 scale “composite” breakwater, based on a prototype 5x5m concrete structure lying on a cohesionless fine marine sand submerged to a depth of 4m. The prototype represents a typical marine structure, as well as a strong resemblance to a common geotechnical system (strip footing) and is assumed to constitute a 2D (plane-strain) problem. The model is subjected to an impact by long-period large amplitude wave (100s, 2m at prototype scale), based on a “Tsunami-like” waveform. This wave is generated by an innovative “Miniaturised Tidal Generator” (MTG) which was specially designed with geotechnical modelling in mind (Jones & Anastasopoulos, 2020). The structure is monitored through a combination of ultrasonic sensing and high-speed photography. Using the “Partial Image Velocimetry” (PIV) method (Stanier et al., 2016), movements of the structure as well as detailed strain fields within the soil can be calculated (Figure 2). Further image analysis allows the computation of the deformed surface profile of the soil.
Figure 2. Prototype breakwater (top-left) and experimental model (top-right) showing high speed camera and targets used for image analysis with PIV. Computed shear strains within the soil (Bottom) are shown for 3 time instances.

Upon impact and overtopping by the wave, the development of a large scour hole is observed, along with some small rotation of the breakwater. Large shear strains develop in the soil before a rapid “failure” of the breakwater, where the concrete system rotates into the newly developed scour hole. In addition, we see changes in volumetric strains within the soil, pre-failure, which indicate a signifant change in the state (and therefore mechanical behaviour) of the soil. Both of these phenomena are not accounted for in current design techniques and represent a significant paradigm shift in the way we understand the behaviour of such structures.

REFERENCES
7.16
Seismic response of a structure on liquefiable soil

Konstantinos Kassas1, Orestis Adamidis2, Nikos Gerolymos3 & Ioannis Anastasopoulos1

1 Institute for Geotechnical Engineering, ETH Zurich, Stefano-Franscini-Platz 5, CH-8093 Zurich (kkassas@ethz.ch)
2 St Catherine’s College, University of Oxford, Oxford, UK
3 Geotechnical Department, National Technical University of Athens, Greece

Buildings founded on shallow foundations on liquefiable soil layers may experience significant settlement and tilt, and can even suffer complete bearing capacity failure. Although such structures are the most common, they are not sufficiently protected, as showcased during a recent major earthquake in Indonesia (Sassa & Takagawa, 2019). The state of practice for the prediction of liquefaction-induced settlement typically relies on free-field methods. Such methods focus on consolidation in the absence of the structure, ignoring the shear strains in the vicinity of the foundation (due to the dead load of the structure) and soil–structure interaction (Dashti et al., 2010). However, experimental evidence from centrifuge model tests has shown that the settlement of such structures is primarily due to shear strains, while sedimentation and consolidation are of minor significance (Adamidis & Madabhushi, 2018).

Despite the valuable insights gained from such centrifuge experiments, a comprehensive study of the problem through centrifuge modelling is resource-demanding due to the large number of parameters that need to be investigated. A more viable option is the use of nonlinear numerical deformation analyses (NDAs), employing advanced constitutive models that can capture the nonlinear stress–strain response of liquefiable soil.

This study employs nonlinear, coupled hydromechanical, effective stress, dynamic, time history analysis to study the seismic response of a structure on a shallow mat foundation, resting on a shallow layer of loose Hostun HN31 sand. The analysis is performed employing the advanced constitutive model PM4Sand (Boulanger & Ziotopoulou, 2017), as implemented in the finite-difference (FD) code FLAC. The constitutive model is thoroughly calibrated versus an extensive set of element tests, which were performed at the ETH Zurich geotechnical laboratory (Kassas et al., 2020). The calibrated model is then validated using one of the centrifuge experiments of Adamidis & Madabhushi (2018) as benchmark.

In Fig. 1, the computed total displacement and shear strain contours at the end of shaking are compared to those of the centrifuge model test, calculated using image analysis (Adamidis & Madabhushi, 2018). The numerical simulation predicts the mobilisation of a bearing capacity failure mechanism, which mainly forms directly below the edges of the foundation, while the magnitude of shearing in the soil bellow the centre of the foundation remains low. The comparison between the total co-seismic displacements developed in the liquefiable layer is also favourable. Both the amplitude and the geometry of the displacement field are well predicted.

The thoroughly validated numerical analysis method (against several centrifuge model tests) is consequently employed to conduct a study, exploring the influence of the container type (rigid, laminar container) on the response. It is also determined the necessary distance of the lateral boundaries to minimize the boundary effects.

Figure 1. Comparison between numerical analysis and centrifuge experiment at the end of the seismic excitation: (a) accumulated total displacement contours; (b) accumulated shear strain contours
REFERENCES


7.17  
**A Scenario-based fragility model for Swiss buildings**

Alireza Khodaverdian*, Pierino Lestuzzi*

* Ecole Polytechnique Fédérale Lausanne (EPFL), Station 18, CH-1015 Lausanne, Switzerland.  
(alireza.khodaverdian@epfl.ch)

Seismic risk assessment at a regional/urban scale is of worldwide concern as the related human or financial losses due to a catastrophic event have a significant societal impact. Although large-magnitude earthquakes are not frequent in Switzerland, several studies (e.g., Lestuzzi et al., 2016) showed buildings, especially ones located in the areas with relatively high seismic hazard, are vulnerable to earthquakes. A fragility model, which covers different building classes with Swiss-specific characteristics, plays a major role in a realistic estimate of damages/losses. In this context, we here focus on Swiss building classes with different load bearing systems and heights; the corresponding fragility curves, which link the different damage grades to spectral ordinates, are generated using the conditional spectrum (Michel et al., 2018) for different scenarios. The obtained results showed that damages are dependant to earthquake magnitude. Considering a large variety of expected earthquake magnitude in Switzerland, the proposed scenario-based fragility model, hence, provides us with a better picture of consequences for each individual possible event and public authorities could benefit from that for real-time loss assessment.

**REFERENCES**


We present our experience in site selection and inspection, array design and deployment of Ocean Bottom Seismometers (OBS) in Lake Lucerne (Switzerland). The challenges related to the OBS localization offshore were addressed by combining multibeam bathymetry and differential GPS coordinates of the OBS at recovery. Two data pre-processing algorithms were developed. The first one was used to correct for the clock drift of the instrument and the second to correct the instrument misorientation. In total, OBS were deployed at over 160 locations on selected subaqueous slopes. The power spectral density curves are estimated and interpreted to derive the Low and High Noise Model for the entire lake. The performance of the array to detect seismic events was assessed by comparing local (Figure 1) and teleseismic events recorded by onshore permanent Swiss Strong Motion stations and offshore OBS. The power power spectra and Peak Ground Velocity (PGV) for recorded earthquakes were also compared and show high values offshore. By processing earthquake recordings using empirical spectral modelling (Edwards et al., 2013), the site amplification functions offshore are obtained and indicate large values compared to observations onshore. Furthermore, the orientation-corrected data were used to perform wavefield polarization analyses from local events using the receiver function principle. By analyzing microtremor data, the spatio-temporal variation of the horizontal-to-vertical (H/V) spectral ratio is assessed. Results show a sensitivity to changes in the local structure and the H/V curves are stable for a 24 hour-record. Finally high quality phase velocity dispersion curves for Scholte and Love waves are estimated.

REFERENCES
Figure 1. Seismograms of the Montreux M4.2 local earthquake that shook Switzerland on 28.05.2019 with over 600 citizen responses (Marti, 2020). The event was recorded on nine (09) OBS offshore four (04) stations onshore (CH network). The station locations are indicated. The data are corrected for both the sensitivity and the instrument response. The represented ground motion is in nm/s.
In-situ estimation of rocking stiffness of pile groups

Alexandru Marin*, Ioannis Anastasopoulos*

*Institute for Geotechnical Engineering, ETH Zurich, Stefano-Franscini-Platz 5, CH-8093 Zürich (amarin@ethz.ch)

An in-situ method for the estimation of rocking stiffness of existing pile groups is highly desirable in the framework of performance-based design and improved evaluation of seismic performance of existing structures. This numerical study explores the possibility of developing such a method based on measurements of lateral vibration induced by low-amplitude non-destructive dynamic loading. The testing equipment required for real-scale applications consists of a mass vibrator at the top of the bridge pier and a measurement tool to record the lateral vibration response of the pier and the rotation of the cap (Fig. 1a).

The proposed measurement estimation method is based on a simplified model of the general problem (Fig. 1c): a series of three spring-dashpot-mass assemblies, representing equivalently the three main lateral motion components of the bridge pier illustrated in Fig. 1b (i.e., swaying $\delta_h$, rocking $\delta_r$, and bending $\delta_f$). The stiffness parameters of interest $K_f$ and $K_r$ can be estimated using Eq. 1, derived from the equations of motion of the simplified model.

$$K_f = \frac{F(t) - m_f \delta - c_f \delta_f}{\delta_f} \quad K_r = \frac{F(t) - m_r \delta - m_r (\delta_h + \delta_r) - c_r \delta_r}{\delta_r} h^2$$

The accuracy of the stiffness estimation equations is evaluated using a three-dimensional numerical model (Fig. 2) of an idealized, yet representative system: a 2x1 pile group ($L_{pile} = 15 m$; $D_{pile} = 1 m$) connected with a rigid pile cap, supporting an 8 m high bridge pier ($D_{pier} = 1.5 m$). The response of the reinforced concrete elements is considered elastic ($E = 30 GPa$), taking into account the low amplitude of the dynamic load (non-destructive testing). The soil profile assumed is a uniform clay of $s_u = 100 kPa$, modelled with a kinematic hardening model with Von Mises failure criterion and associated flow rule (Anastasopoulos et al., 2011).
Figure 1. Details of the three dimensional model of the analysed problem.

The measurement estimates of the flexural and rocking stiffness parameters $K_f$ and $K_r$, obtained by introducing in Eq. 1 the numerically simulated motion parameters, are compared with their real values, obtained from lateral pushover tests performed with the same FE model. The comparison indicates that the estimated values coincide with the real ones, and the proposed method can be used to evaluate the structural health (i.e., $K_f$ of existing piers) and to estimate the real rocking stiffness (i.e. $K_r$) of existing pile groups. Nevertheless, further numerical and experimental investigations are required to generalize the results of this study and implement the estimation method to real-scale applications.

Figure 2. Three dimensional model of the analysed problem with the adopted loading function.

REFERENCES

AIT, 2020: Mobile seismic simulator. Austrian Institute of Technology - Center for Mobility Systems, Vienna, Austria.


Towards building-typology formulations that are adapted for structural health monitoring applications

Panagiotis Martakis*, Yves Reuland*, Eleni Chatzi*

*Dept. of Civil, Environmental and Geomatic Engineering, ETH Zurich, Stefano-Franscini-Platz 5, CH-8093 Zürich (martakis@ibk.baug.ethz.ch)

Earthquakes are disruptive events that cause widespread damages to the built environment and carry a high societal loss potential. In addition to direct losses, unavailable buildings and other infrastructure components undermine normal functioning for an extended period after the earthquake and ultimately hinder recovery. While enforcing modern building codes is a cornerstone of risk reduction, knowledge of the vulnerability of the building stock at large scale is key to enable optimal planning of retrofitting before earthquake events and emergency interventions immediately after the event. When coping with thousands of buildings, taxonomies of building types (Brzev et al. 2012) are an essential tool. However, classical taxonomy formulations and vulnerability curves of building types are based on highly simplified behavior models and very rudimental building characteristics, such as year of construction, building material and number of floors above ground (Lestuzzi et al. 2016). Although such data sources have the advantage of being well-documented in national databases (at least in developed countries), they are often not compatible with the degree of precision offered by modern tools, such as measurement devices and image-processing algorithms.

Another drawback of existing typological formulations (such as capacity curves or fragility curves) is related to missing out on key contributors to seismic deficiency. For instance, irregularities in plan and elevation, amount of openings, type of roof and foundations, are rarely part of simplified vulnerability classes. In addition, modal properties, such as natural periods and mode shapes, carry a lot of information regarding building responses to earthquake loads. With improved availability of efficient sensing solutions, modal properties can be retrieved with relative ease and speed.

Therefore, in this contribution, authors study the influence of characteristics of the Swiss building stock on the seismic capacity. With the help of parametrized physics-based models, clusters of behavior are analysed in order to discuss the most important properties that influence predicted seismic behavior (namely yield displacement, ultimate displacement and the safety coefficient described in Swiss codes (SIA 266, SIA269/8). As permanent installation of sensors is unlikely to be achieved systematically in all buildings, especially in regions with low-to-moderate seismic hazard, a performance-based building categorisation is key to choose indicator buildings for efficient and large-scale implementation of structural-health monitoring for rapid post-earthquake assessment. Through improvements of preparedness and rapid disaster response, such large-scale structural health monitoring tools can improve societal resilience with respect to earthquakes and, within the Swiss context, could refine the seismic risk model currently under preparation (Roth et al, 2018).

REFERENCES
7.21
The effect of declustering on the size distribution of mainshocks

Leila Mizrahi*, Shyam Nandan*, Stefan Wiemer*

*Swiss Seismological Service, ETH Zürich, Sonneggstrasse 5, CH-8092 Zürich (leila.mizrahi@sed.ethz.ch)

Declustering algorithms aim to divide earthquake catalogs into mainshocks and dependent (clustered) events such as fore- or aftershocks. Many seismicity studies, including seismic hazard assessment for Switzerland, are based on declustered catalogs. They consist solely of mainshocks to avoid spatial biases due to seismicity clustering.

Several declustering algorithms have been proposed and used, and, as earthquakes do not come with labels, there is no objective criterion with which to evaluate the performance of the different methods.

We assess the effect of declustering on the frequency-magnitude distribution of mainshocks, described by the empirical Gutenberg-Richter (GR) law (Gutenberg and Richter, 1944). In particular, we examine the dependence of the $b$-value of declustered catalogs on the choice of declustering approach and algorithm-specific parameters. Using the catalog of earthquakes in California since 1980, we show that the $b$-value decreases by up to 30% due to declustering with respect to the undeclustered catalog. The extent of the reduction is highly dependent on the declustering method and parameters applied. Window methods (Gardner and Knopoff, 1974), in particular with Gruenthal window parameters (Gruenthal, 1985) which are used for the 2015 Swiss seismic hazard model, induce a relatively large $b$-value reduction among the methods considered.

In the second part of this study, all the above-described effects are reproduced in synthetic data by declustering simulated earthquake catalogs with known $b$-value, which have been generated using an Epidemic-Type Aftershock Sequence (ETAS) model.

Our analysis suggests that the observed decrease in $b$-value must, at least partially, arise from the application of the declustering algorithm on the catalog, rather than from differences in the nature of mainshocks versus fore- or aftershocks. Thus, $b$-values of declustered catalogs are biased to a somewhat arbitrary and not immediately apparent extent. This bias can lead to an overestimation of seismic hazard. We conclude that declustering should be considered as a potential source of bias in seismicity and hazard studies, which could be avoided for example by using ETAS based long-term forecasts.

Figure 1: (a) $b$-value versus $a$-value of the declustered California catalog depending on declustering method and parameters. Each dot represents one variation of parameter settings, stars with error bars represent standard parameter settings. Marked with (W) are window methods. The dotted grey line and grey area indicate the $b$-value of the non-declustered catalog and its uncertainty. (b) Distribution of mainshock $b$-values of 2000 simulated catalogs, depending on declustering method (with standard parameter settings and standard (Gardner-Knopoff) window), plotted against median $a$-value per method. Stars with error bars represent the $b$- and $a$-value of the regional earthquake catalog from (a) for the respective methods. The dotted line displays the $b$-value used for catalog generation, which corresponds to the full-catalog $b$-value observed in the Californian primary catalog.
REFERENCES
7.22
Reconstruction of site amplification functions through canonical correlation with site proxies

Francesco Panzera1, Paolo Bergamo1 & Donat Fäh1

1Swiss Seismological Service, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich (francesco.panzera@sed.ethz.ch)

Site specific seismic hazard assessment needs a ground motion amplification model of the investigated region. This model allows to highlight areas that can be strongly affected by earthquake ground motion, which is a crucial information for earthquake mitigation.

Empirical site response can be investigated by using technique such as standard spectral ratio (SSR; Borcherdt, 1970), empirical spectral modelling (EAF; Field and Jacob, 1995; Edwards et al., 2013) or indirectly through analysis of horizontals-to-vertical spectral ratio (HVSR; Nakamura, 1989). The first two techniques SSR and EAF are the most powerful, because they allow to retrieve the amplification function of the investigated site by using earthquake recordings, but they require a long observation time to record a sufficient number of earthquakes. The HVSR method is instead a simplified method based on the ambient vibration recordings. It allows to retrieve information on fundamental frequency and amplitudes of HVSR as a function of frequency in a first step, and to estimate ground motion amplification in a second step. We propose such method to retrieve amplification information based on the correlation of geological, topographical and geophysical proxies (HVSR and Vs30 from measured shear-wave velocity profiles) with EAF measured at a set of instrumented sites. We apply canonical correlation (cc) as suggested by Cultrera et al. (2014). The cc technique investigates the correlation between two sets of variables by identifying their linear combinations having maximum correlation (Davis, 2002). For this purpose 172 free-field and urban free-field seismic station sites with available EAF, HVSR, and velocity profiles were used. The estimated cc coefficients are then used to reconstruct the expected EAF at sites where site proxies are available (see example in Fig. 1).

![Figure 1. Comparison between observed amplification (red) and the predicted amplification (blue) obtained using cc coefficients for the SSMNet station SDAK. Left panel shows the predicted amplification in 9 frequency bins, whereas right panel displays results for 16 bins.](image)

The results of our analysis highlighted the ability of the method to provide an estimate of the site amplification over a chosen set of frequency bins starting from simple geological, topographical and geophysical proxies (e.g. HVSR and Vs30). Finally, the method can be used to estimate amplification information at sites where ground motion amplification is not measured. We present an application for the site Visp in the Rhone valley.

REFERENCES


Exposure aggregation strategies for efficient assessment of seismic risk in Switzerland

Athanasios Papadopoulos*, Philippe Roth*, Laurentiu Danciu*

*Swiss Seismological Service, ETH Zurich, Sonneggstrasse 5, CH-8092 Zurich (athanasios.papadopoulos@sed.ethz.ch)

Exposure models for regional seismic risk assessment are typically defined at a rather crude resolution. In most cases, precise exposure locations are difficult to determine and model developers have to work with data available at administrative unit or ZIP-code levels. At best, these data are then disaggregated, leveraging upon proxy datasets such as the distribution of population or the density of night-time lights (Silva et al. 2020). The final resolution of the exposure model is either dictated by the resolution of the proxy dataset, or chosen by the modeler in line with the available computational resources. To build the exposure model of the 2022 ERM-CH model, the workflow is reversed, given the availability of an extensive building-by-building database for the Swiss territory, which however needs to be aggregated to ensure plausible risk calculation runtimes. The objective is thus to minimize the number of exposure locations, while achieving the best possible trade-off between accuracy and computational efficiency.

Exposure aggregation might introduce error in different ways (Bal et al. 2010; Bazzurro & Park 2007). For instance, the relocation of assets might move them further away or closer to seismogenic sources capable of inducing significant or frequent losses. Similarly, it can place them at locations with different site conditions, where they will be modelled to experience smaller or larger amplification of ground motion or macroseismic intensity. The latter is particularly relevant for the ERM-CH model for which high-resolution site amplification maps are developed. For large exposure datasets, such errors are often averaged out, yet they might still be pronounced depending on factors such as the size and spatial distribution of the exposure, the resolution of the aggregation, and the granularity of the source and site effect models. Aggregation can also introduce an artificial correlation on the input intensity of the assets aggregated together, which might result in a decrease of loss estimates at low return periods and an increase at larger return periods.

Herein, we present a preliminary investigation using a subset of the ERM-CH building database comprising 1,754,875 buildings distributed across the country. The building database was aggregated on three alternative grids with resolutions of 2 km x 2 km, 1 km x 1 km, and 0.5 km x 0.5 km. Moreover, three alternative strategies were explored: (a) aggregation at the centroid of each grid cell, (b) aggregation at the centroid of each grid cell but assigning to that location the intensity amplification factor that is the most prevalent across the real locations of the buildings, and (c) aggregation like in (b) but without aggregating the buildings comprising the top 5% of the exposure model in replacement cost. Comparisons of average annual loss (AAL) estimates obtained using each of these strategies and a non-aggregated exposure are reported for the cantons of Zurich and Valais. At the cantonal level, the effect of aggregation on risk estimates seems to be limited due to the averaging out of errors at individual grid cells. However, at ZIP-code level, our results indicate that an aggregation resolution of 2 km x 2 km should probably be avoided (see Figure 1).

Moreover, as shown in Figure 2, assigning to each location an amplification factor that best reflects the real locations of the buildings aggregated therein, i.e. strategy (b), seems to yield a substantial error reduction. On the other hand, not aggregating the most valuable buildings, i.e. strategy (c), results in just modest gains for the considered exposure dataset.
REFERENCES


7.24
Empirical Earthquake’s Site Response Assessment In The Sion Area, Switzerland

Vincent Perron*, Paolo Bergamo*, Francesco Panzera*, Conny Hammer* & Donat Fäh*

* Swiss Seismological Service (SED), ETH Zürich, Sonneggstrasse 5, CH-8092 Zürich, Switzerland (vincent.perron@sed.ethz.ch)

The Sion area in Canton Valais is one of the most seismically active areas of Switzerland. Moreover, the thick and soft sedimentary deposits of the Rhône valley are prone to increase significantly both the amplitude and the duration of the seismic signal. This study aims to evaluate the so-called “site effects” in Sion area in order to better define the seismic hazard locally. It is carried out in the framework of the “Site Response” module of the “Earthquake Risk Model for Switzerland”.

Five long-term seismic stations were deployed in addition to four permanent stations of the Swiss Strong Motion Network (SSMNet) already present in the area of Sion. Several tens of mostly local and small magnitude earthquakes were recorded successfully at these nine stations, including those of the 2019 seismic cluster north of Sion. This allows the use of the Empirical Spectral Modelling (ESM) approach of Edwards et al. (2013) at these nine stations. This approach accounts for the source and for the propagation term of the ground motion in order to provide amplification values with respect to the Swiss rock reference (Poggi et al., 2011). The site response is also estimated locally at seven stations by performing Standard Spectral Ratios (SSR - Borcherdt, 1970) with respect to two of the stations located on rock that are used as references, assuming that the source and the propagation term are similar for close stations.

In order to estimate site effects with high spatial resolution, a very dense measurement campaign was performed in 2019 in the area of Sion, along the Rhône valley from Vétroz to Saint-Leonard. Ambient vibrations were recorded for about 1h at around 300 points of a 250 m side grid. A detailed map of the fundamental frequency of resonance of the soil can be deduced from these measurements using the Horizontal-to-Vertical Spectral Ratio method (HVSR, Nakamura 1989). It helps addressing the spatial distribution of the seismic-wave resonance in the Rhône valley, and it is used to improve the resolution of the geological model locally. Moreover, we attempt to assess the site amplification with high spatial resolution at every frequency by applying the hybrid SSR techniques (SSRh - Perron et al., 2018). This approach uses the spectral ratio of ambient vibration recorded between stations located inside the sedimentary valley to estimate the spatial variation of the site response, and the classical SSR based on earthquakes recorded at few stations only to make the rock referencing.

For sites where both the SSR and the SSRh could be computed, a good agreement is found between the two approaches. Moreover, the fundamental resonance frequency model, and the amplification model are consistent with the geological model proposed by Swisstopo for the area of Sion. This is confirming the validity of analysing ambient vibration to determine both the fundamental resonance frequency and the amplification function of the sites. Amplification factor up to 12 are observed for frequency higher than 0.5 Hz along the Rhône valley in the area of Sion. Such amplification of the seismic waves drastically increase the seismic hazard in some parts of the city of Sion. From the measurements, we also propose a site for a new permanent seismic station in the SSMNet renewal project, which shows high amplifications due to shallow layers with very soft sediments, which can be found at some sites in the region of interest.

Figure 1 Map of the Sion area. The red triangles are the permanent stations of the SSMNet, the orange triangles long-term stations and the green dots represent the location of the 1h ambient vibration recording. The colormap represent the amplitude of the HVSR at 0.5 Hz which is the fundamental resonance frequency at the centre of the Rhône valley (the deeper the blue the higher the amplitude).
REFERENCES


7.25
Modelling of RC pilegroups under seismic loads

Antonia Psychari*, Athanasios Agaianos*, Lampros Sakellariadis*, Ioannis Anastasopoulos*

* Institute for Geotechnical Engineering, ETH Zurich, Stefano-Francini-Platz 5, CH-8093 Zurich
(antonia.psychari@igt.baug.ethz.ch)

Realistic finite element (FE) modelling of the dynamic response of pilegroups calls for reasonably accurate modelling of reinforced concrete (RC) nonlinear response. In practise, RC piles are commonly modelled with nonlinear beam elements, approximating their nonlinear response with moment-curvature relations (M-c model), according to section analysis for an assumed axial load. A hybrid modelling technique (Kourkoulis et al. 2011) combines nonlinear beam elements, positioned along the pile axis, with dummy continuum elements (of zero stiffness) modelling the pile periphery. Appropriate kinematic constraints ensure the deformation of each pile section as a disk.

In the case of pilegroups, the main resisting mechanism to the applied seismic loads is through axial loading of the piles. As a result, the level of axial loading of each pile varies significantly during a seismic event and the aforementioned M-c model constitutes an approximation, as it assumes a constant axial load, neglecting the interaction between axial load (N) and moment capacity (M).

In the current study, the piles are modelled in a more rigorous manner with 3D nonlinear continuum elements, employing the Concrete Damage Plasticity (CDP) model, which is readily available in Abaqus (ABAQUS 2012). Appropriate material properties are defined to account for the confined concrete core and the unconfined cover concrete (Mander et al. 1988; Chang & Mander 1994). The longitudinal reinforcement of the piles is modelled with shell elements. In addition, damage parameters per level of inelastic response are defined to capture the crashing or cracking of elements within the pile cross section. The model is capable of capturing not only the N-M-interaction, but also the cumulative damage of the plastic hinge during consecutive load cycles.

In order to comparatively assess the two modelling techniques, two simple 2x1 pilegroups are considered, varying the pile length from 10 m to 20 m (Fig. 1a), assuming a pile diameter of 1 m, pile spacing of 3 m, concrete C25/30 and 1% reinforcement ratio. The pilegroups are modelled employing both techniques (M-c and CDP). The pilecap is assumed elastic and a rigid pier of 9 m height is considered. In both cases, the soil is assumed to be homogeneous clay with undrained shear strength $S_u = 100$ kPa, modelled with a thoroughly validated kinematic hardening model, with a Von Mises failure criterion and associated flow rule (Anastasopoulos et al. 2011). Tensionless, frictional interfaces are introduced between the soil and the foundation members. The assumed static load acting on the pilegroup (superstructure dead load) corresponds to 50% of its vertical bearing capacity (corresponding to a factor of safety of 2). The pilegroups are subjected to displacement controlled horizontal pushover analysis, with the displacement applied at the pier top.

The two modelling techniques are compared in terms of moment-rotation ($M-\theta$) response (Fig. 1b). The performance of the short pilegroup is almost insensitive to the employed modelling technique, as the response is dominated by the external (soil) axial bearing capacity of the piles (Fig. 1c). This is not the case for the longer pilegroup, where the axial capacity of the leading pile (under tension) is dominated by its internal capacity (RC failure). Since the M-c model does not account for N-M-interaction, the RC failure of the leading pile is not captured, leading to 20% overestimation of pilegroup capacity (Fig. 1b). This confirms the need for realistic modelling of RC nonlinear response.
Figure 1. Monotonic pushover response of short (top) and long (bottom) pilegroup: (a) FE model; (b) moment-rotation (M-θ) response; and (c) pile axial response (and comparison with analytical solutions: dashed lines).

REFERENCES


7.26
A first step to assess subaquatic mass movement hazards in lakes

Love Rāman Vinnā1,2, Damien Bouffard2, Alfred Wüest1,2, Stéphanie Girardclos3,4, Nathalie Dubo15,6
1 Physics of Aquatic Systems Laboratory – Margaretha Kamprad Chair, Institute of Environmental Engineering, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland (love.ramanvinna@eawag.ch)
2 Eawag, Swiss Federal Institute of Aquatic Science and Technology, Surface Waters – Research and Management, Kastanienbaum, Switzerland
3 Department of Earth Sciences, Université de Genève, Genève, Switzerland
4 Institute for Environmental Sciences, Université de Genève, Genève, Switzerland
5 Department of Earth Sciences, ETH Zürich, Zürich, Switzerland
6 Eawag, Swiss Federal Institute of Aquatic Science and Technology, Surface Waters – Research and Management, Dübendorf, Switzerland

Shorelines of both inland and coastal waters are often highly altered geomorphological environments that accommodate major infrastructure including harbors, roads, railways, underwater pipelines, transmission cables and water intakes. Slope failures resulting in massive, rapid downslope movement of sediment, also known as subaquatic mass movements, can damage this infrastructure and disrupt lake ecosystems. Subaquatic mass movements can also cause major property damage around lakes. Examples are plentiful and include the destruction of multiple houses and quays around Lake Geneva during the 18th and 19th centuries (Forel 1892, p.148-151). Subaquatic mass movements are known to have disrupted settlements surrounding Lake Geneva even during prehistoric times. A tsunami caused by a mass movement may have caused a gap in occupation around the lake during the early bronze age (~1700 BC; Kremer et al. 2014). In early medieval times, a rock fall caused a Rhône delta collapse resulting in a tsunami which passed over the city walls of Geneva (563 AD; Kremer et al. 2012). More recent examples include construction induced slides in Lake Lugano, which damaged the Lugano city port in 1992 (Hofmann & Filella 1999), and the Horgen slide of 1875 (Keits & Hsü 1980), which swept a newly constructed railway into Lake Zürich.

Assessing risk associated with subaquatic mass movements is difficult and depends on accurate prediction of mechanisms that trigger slope failure and likely locations of failure (Harbitz et al. 2014). Recent advances in bathymetric sensing (e.g. multi-beam and LIDAR surveys) have enabled more detailed imaging of high-risk areas. Basin scale evaluation can include methods for estimating risk areas and damages of different risk factors (Strasser et al. 2011; Strupler et al. 2019). Surveys however can usually only gather a limited number of high quality samples. This research used an interdisciplinary hydrodynamic and sedimentological approach to identify areas at risk for subaquatic mass movement in Lake Biel. This was accomplished with both hydrological and Sedimentological in-situ samples combined with 3D hydrological modeling (Delft3D-Flow). The combined datasets revealed both processes driving lake sedimentation and areas at risk for future subaquatic mass movements.
REFERENCES
7.27
Assessing a 6C Kalman filter using experimental datasets from an industrial robot

Yara Rossi *,**, Konstantinos Tatsis***, Konstantin Arbogast*, Mudathir Awadaljeed*, Eleni Chatzi***, Markus Rothacher *, John Clinton **

*Institute of Geodesy and Photogrammetry, ETH Zurich, Robert-Gnehm Weg 15, CH-8093 Zurich (rossiy@ethz.ch)
**Swiss Seismological Service, ETH Zurich, Sonneggstrasse 12, CH-8092 Zurich
***Institute of Structural Engineering, ETH Zurich, Stefano-Franscini-Platz 5, CH-8093 Zurich

Shaking from earthquakes is a complex set of six components (6C) that make up the ground motion, containing both translations and rotations. Nonetheless, state-of-the-art earthquake monitoring stations only include accelerometers and GNSS to record the strong ground motion. The inertial accelerometer sensors directly measure the translational part of the motion, though rotations contaminate this output and are difficult to quantify. GNSS is less sensitive to rotations and can only resolve large amplitudes and long period ground motion. Therefore, the future design of monitoring stations should include a rotational sensor to allow a complete reconstruction of the ground motion. These monitoring stations do not only benefit the reconstruction of the ground motion resulting from earthquakes, but also the reconstruction of the dynamics of large engineered structures due to natural and anthropogenic sources. Switzerland has an abundance of bridges and dams that could largely benefit from a more complete motion sequence.

We have built a monitoring station that combines an accelerometer and rotational sensor, both sampling at 250 Hz, with a GNSS receiver and antenna determining coordinates with a lower sampling rate of 100 Hz. The three instruments have been fixed to a platform attached to the top of an industrial six-axis robot arm, while the arm performs simulated ground motions with high accuracy and repeatability. The robot has its own feedback loop recording position and orientation of the platform. This serves as the ground truth for the performed trajectory. It allows us to compare all the results obtained to the actually performed trajectory of the robot.

We designed a 6C Kalman filter that combines the three instrument records using an optimal equation design and optimal tuning of the parameters. It includes time domain tilt corrections of the acceleration and subsequent estimation and correction of the instrument records to get the state vector consisting of displacement, velocity and rotation. The developed framework and sensing scheme is able to output rotation-free, broadband and precise 3C translations as well as drift-free and precise 3C rotations.
7.28

Numerical study on the moment capacity of typical bridge pile groups on sand

Lampros Sakellariadis*, Daniel Alig* & Ioannis Anastasopoulos*

* Institut für Geotechnik, ETH Zürich, Stefano-Franscini-Platz 5 8093 Zürich

This study investigates the behavior of a simple pile group on sand under pushover loading, employing the Finite Element (FE) method. A parametric study is conducted, exploring the role of vertical safety factor ($F_S$), piles reinforcement ratio ($\rho$), and pier height ($h$). The contribution of the pile cap is also quantified.

ANALYSIS METHODOLOGY: CALIBRATION & VERIFICATION

After evaluation of data of Swiss bridges provided by ASTRA, a 2x1 pile group is studied, consisting of bored piles of length $L = 15m$, diameter $D = 1m$ and spacing $s/D = 3$ on Perth Sand. Figure 1 gives an overview of the FE model in Abaqus. The superstructure is modelled as rigid, while the mass and pier height are varied to study different $F_S$ ($1÷3$) and moment to horizontal loading ratios ($6÷20$). “Heavily” and “lightly” reinforced piles are studied ($\rho = 0.6% - 1%$). The Hypoplastic model (Von Wolffersdorff, 1996), calibrated against triaxial tests, is used to model sand, while the piles are modelled with the Concrete Damaged Plasticity (CDP) model.

Figure 1. Overview and calibration of the FE model in Abaqus.

Initially, a single pile was examined. The load-settlement behavior under axial loading was validated against centrifuge test results and further compared to bearing capacity theory (Fleming et al., 2008). Subsequently, the behavior under lateral loading was verified against the solution of Broms (1964).

PARAMETRIC NUMERICAL STUDY

Example results of the initial study, where the pile cap contribution is ignored, are summarized in Fig. 2. The moment capacity of the pile group is slightly increased with $h$, while the reinforcement ratio $\rho$ has limited effects. The reduction of $F_S$ (i.e., more heavily-loaded foundation) increases the capacity. The contribution of different resisting mechanisms is quantified, showing that the axial loading of the piles is dominant (Fig. 3). In all cases examined, the pullout resistance of the trailing pile is critical, and hence the more heavily loaded system mobilised increased capacity. On the contrary, the role of the “bending” mechanism is limited.
Figure 2. The effect of: (a) pier height $h$; (b) pile reinforcement ratio $\rho$; and (c) safety factor $FS$, on the moment resistance of a 2x1 pile group.

Figure 3. Mobilised resistance mechanisms.

The contribution of the pilecap is quantified, activating its interface (Fig. 4a). Its engagement increases both capacity and stiffness. Focusing on the effect of $FS$, the more heavily-loaded pile group mobilises higher resistance (Fig.4b), while the structural behavior with and without the cap is similar.

Figure 4. (a) contribution of the cap, (b) effect of $FS$ (c) structural performance of the piles with and without the engagement of the cap

CONCLUSIONS
The commonly used $FS$ is not representative of the seismic capacity: heavily-loaded systems mobilise larger moment capacity. The effect of $\rho$, and $h$ is limited when the moment capacity is critical.

REFERENCES
7.29
Revealing the structure of submerged slopes in Lake Lucerne using ambient vibration techniques

Anastasiia Shynkarenko*, Agostiny Marrios Lontsi*, Katrina Kremer*,**, Paolo Bergamo*, Manuel Hobiger*, Miroslav Hallo*, Donat Fäh*

*Swiss Seismological Service, ETH Zürich, Sonneggstrasse 5, CH-8092 Zürich (a.shynkarenko@sed.ethz.ch)
**Geological Institute and Oeschger Centre for Climate Change Research, University of Bern, Baltzerstrasse 1+3, CH-3012, Bern

Seismically and aseismically triggered submerged slope failures in a lake environment can potentially cause a tsunami. Such a phenomenon would pose a significant hazard to the population and infrastructure of quite extensively used lake shores.

To better understand the tsunami hazard related to the submerged slopes in the lakes, we need to know their internal structure and sediment properties. As a study site for such an investigation, we selected Lake Lucerne in Central Switzerland. Tsunamis have occurred repeatedly in Lake Lucerne, for example, in 1601 AD a tsunami was triggered by the Mw 5.9 Unterwalden earthquake. Wave heights of at least 4 m and a subsequent seiche lasting several days are mentioned in historical reports. A repetition of such an event nowadays could cause significant casualties and financial losses.

In this work, we apply non-invasive passive seismic techniques based on the recording of ambient seismic noise to reveal the structure and material properties of the sediment-charged submerged slopes. For this purpose, we deploy arrays of 9 Ocean Bottom Seismometers (OBS) and single OBS stations at potentially unstable slopes (Fig.1a) for periods between 2 days and 9 months. Based on the analysis of recorded ambient seismic noise and earthquake signals, we evaluate the fundamental frequency of resonance and seismic amplifications at the study sites and estimate the Scholte wave ellipticity and the phase velocity dispersion curves of the propagating surface waves. A combined inversion of the ellipticity and dispersion curves allows us to derive the 1D shear wave velocity profiles at the investigated sites (Fig. 1b). Based on the obtained information, we define the sediment-lithological units of the slopes and estimate their thickness and elastic properties.

As the next step of this work, we aim at creating 3D slope models with defined sediment properties for the selected sites in Lake Lucerne.

Fig. 1. a) map of conducted single station (yellow circles) and array (red circles) OBS measurements in Lake Lucerne. The black rectangle marks the location of the array ENA at Ennetbürgen; b) an example of derived shear wave velocity profile below the array ENA with zoom to the upper 20 m: purple and blue lines represent soil models with the maximum probability and minimum misfit, respectively; grey-shaded area marks part of the profile with no data resolution.
Simplified analysis for nonlinear foundation response

Max Sieber*, Ioannis Anastasopoulos*

*Institute for Geotechnical Engineering, ETH Zürich, Stefano-Franscini-Platz 5, CH-8093 Zürich
(max.sieber@igt.baug.ethz.ch)

Recent research on soil-structure interaction of structures subjected to seismic loading led to the recognition that strongly nonlinear soil-foundation response may have a beneficial effect on structural integrity. Such strongly nonlinear soil-foundation response can be used for seismic protection of structures, leading to the development of a novel design concept, termed “rocking isolation” (Anastasopoulos et al., 2010 & 2013; Gajan et al., 2005; Gajan & Kutter, 2008; Mergos & Kawashima, 2005). Unlike conventional design, where failure is guided to the superstructure, rocking isolation guides failure to the soil (Fig. 1). Rocking isolation simply implies allowing a surface foundation to uplift and fully mobilize its bearing capacity (soil failure). Both effects limit the inertia loading of the superstructure and therefore act as a safety valve protecting the superstructure. Particularly for large intensity earthquakes, that clearly exceed the design limits, this novel design concept shows excellent performance. In practise, rocking isolation can be applied simply by reducing the foundation dimensions.

However, the performance assessment of such rocking–isolated structures (needed for their design) can be challenging, since it requires nonlinear dynamic time history analysis. Therefore, there is a need for simplified analysis methods that are computationally efficient, simple in application and capable of predicting with reasonable accuracy the nonlinear foundation response. The present study investigates the robustness of three simplified analysis methods that differ in complexity and idealization. The methods are assessed by comparison with nonlinear finite element (FE) time history analysis of a single bridge pier supported on a shallow square foundation, lying on a stiff undrained clay stratum. The FE model encompasses the entire soil-foundation-structure interaction.

REFERENCES
Shake table testing of aggregate masonry buildings

Igor Tomić*, Andrea Penna**, Matthew DeJong***, Christoph Butenweg****, António Correia*****; Paulo Candeias******, Ilaria Senaldi**, Gabriele Guerrini*******; Daniele Malomo*** & Katrin Beyer*

*École Polytechnique Fédérale de Lausanne (EPFL), School of Architecture, Civil and Environmental Engineering (ENAC), Earthquake Engineering and Structural Dynamics Laboratory (EESD), Lausanne, Switzerland, igor.tomic@epfl.ch
**University of Pavia, Department of Civil Engineering and Architecture (DICAr), Masonry Structures Section, Pavia, Italy
***University of California Berkeley, Civil and Environmental Engineering, Berkeley, United States
****RWTH Aachen University, Center for Wind and Earthquake Engineering, Aachen, Germany
*****National Laboratory for Civil Engineering (LNEC), Lisboa, Portugal
******EUCENTRE European Centre for Training and Research in Earthquake Engineering, Pavia, Italy

Masonry building aggregates can be found throughout historical city centers of Europe. Adjacent buildings have often developed during the long densification process, without consistent planning or engineering. It is common for neighboring units to share a structural wall with the connection between the units ensured through interlocking stones or a dry joint. Another consequence of the gradual development through the years are the different material properties, distributions of openings, and different roof and floor heights of the neighboring units. The difference in properties and the uncertainty related to the connection between the units leads to difficulties when modelling the seismic response. For that reason, units of an aggregate are often modelled as separate or perfectly connected. Both simplifications can lead to an incorrect estimation of the aggregate response. One of the principal reasons impeding the advancements in this area is the lack of large-scale experimental campaigns, due to the size and the cost of such campaigns. For that reason, the project AIMS (Seismic Testing of Adjacent Interacting Masonry Structures), included in the H2020 project SERA has the objective to provide the experimental data on the behaviour of an aggregate of two stone masonry buildings under bi-directional horizontal acceleration. The test unit is constructed at half scale, with one storey building and a two-storey building. The buildings share one common wall and the façade walls are connected by dry joints. Units have different floor heights and floor beam orientations, leading to a complex dynamic response. The shake table test is conducted at the LNEC seismic testing facility. Extensive instrumentation, including an optical displacement measurement system, displacement transducers, and accelerometers are used to provide information on the force-displacement response. Special attention is devoted to the interface opening and the global behaviour in relation to the interface separation.

Figure 1. Test unit
Seismic Response of Underground Metro Station: Shake Table Testing and Numerical Simulation

Weifeng Wu*, Shiping Ge*, Yong Yuan*, Wenqi Ding*, and Ioannis Anastasopoulos**

* Department of Geotechnical Engineering, Tongji University, Siping Road 1239, 200092 Shanghai, P.R. China
(weifeng.wu@igt.baug.ethz.ch)
** Institute for Geotechnical Engineering, ETH Zürich, Switzerland

The seismic response of underground structures has lately received increased attention, due to their severe damage or even collapse in recent major seismic events. This study investigates the seismic performance of a representative 2-storey, 3-span Shanghai Metro station in soft soil, combining 1g shaking table testing and numerical analysis. To remedy the problem of scale effects in 1g testing, synthetic model soil (a mixture of sand and sawdust) is used, along with similitude relations derived considering dynamic equilibrium. The properties of the synthetic model soil are adjusted to satisfy similitude, including stiffness and density. The structure is modelled using granular concrete and galvanized steel wires (Wu et al. 2020). As shown in Figure 1, accelerometers, wire displacement transducers and earth pressure transducers were installed to measure the seismic response of the tunnel and soil. To quantify the transferability of the results to prototype scale, the experiments are simulated with nonlinear finite elements (FE), modelling the synthetic model soil with an extended kinematic hardening constitutive model. The model was calibrated for the model soil using the results of resonant column and direct shear tests. In this way, the 1g shaking table tests served as a benchmark for model validation. The FE model was shown to compare well with the shaking table tests in terms of acceleration time histories and amplification. Larger discrepancies were observed when examining soil pressures on the station sidewall, which, however, may be due to measurement errors rather than modelling inaccuracies.

Figure 1. Shaking table model layout, showing geometry and instrumentation (detailed scheme of strain gauges on the tunnel is not included.

The validated FE model is subsequently used to predict the seismic response of the prototype, allowing indirect transfer of the results from model to prototype scale. As shown in Fig. 2, moving from model to prototype scale, the inter-storey drift remains qualitatively similar, but reduces by 50%. This is partly due to scale effects, but also related to differences between the idealized soil of the experiments and the multiple soil layers of reality. The maximum bending moment reduces by 30% going to prototype scale. The base of lower-storey columns is proven to be the most vulnerable, as was the case for the collapse of the Daikai Metro station during the 1995 Kobe earthquake (An et al., 1997).
Figure 2. Numerical results of maximum racking deformation (drift) and bending moments: (a) shake table test; (b) idealized prototype; and (c) prototype.

REFERENCES
Wu, W., Ge, S., Yuan, Y., Ding, W., & Anastasopoulos, I. 2020: Seismic response of subway station in soft soil: Shaking table testing versus numerical analysis, Tunnelling and Underground Space Technology, 100, 103389.
P 7.1

Physics-based Earthquake Source Models for Seismic Engineering: Analysis and Validation for Dip-slip faults


* AECOM, USA. (percy.galvez.barron@gmail.com)
** Geo-Research Institute, Osaka, Japan.
*** KAUST University, Saudi Arabia.

Physics-based dynamic rupture modelling is necessary for estimating parameters such as rupture velocity and slip rate function that are important for ground motion simulation, but poorly resolved by observations, e.g. by seismic source inversion. In order to generate a large number of physically self-consistent rupture models, whose rupture process is consistent with the spatio-temporal heterogeneity of past earthquakes, we use multicycle simulations under the heterogeneous rate-and-state (RS) friction law for a 45deg dip-slip fault. We performed a parametrization study by fully dynamic rupture modeling, and then, a set of spontaneous source models was generated in a large magnitude range ($M_w > 7.0$).

In order to validate rupture models, we compare the source scaling relations vs. seismic moment $M_o$ for the modeled rupture area $S$, as well as average slip $D_{ave}$ and the slip asperity area $S_a$, with similar scaling relations from the source inversions. Ground motions were also computed from our models. Their peak ground velocities (PGV) agree well with the GMPE values. We obtained good agreement of the permanent surface offset values with empirical relations.

From the heterogeneous rupture models, we analyzed parameters, which are critical for ground motion simulations, i.e. distributions of slip, slip rate, rupture initiation points, rupture velocities, and source time functions. We studied cross-correlations between them and with the friction weakening distance $D_c$ value, the only initial heterogeneity parameter in our modeling. The main findings are: (1) high slip-rate areas coincide with or are located on an outer edge of the large slip areas, (2) ruptures have a tendency to initiate in small $D_c$ areas, and (3) high slip-rate areas correlate with areas of small $D_c$, large rupture velocity and short rise-time.
P 7.2
Crustal Structure imaged by 3-D Seismic Attenuation for the Central Alps and their Foreland

Federica Lanza*, Tobias Diehl*, Marco Herwegh** & Stefan Wiemer*

* Swiss Seismological Service, Swiss Federal Institute of Technology, ETH Zurich, Sonneggstrasse 5 CH-8092 Zurich (federica.lanza@sed.ethz.ch)
** Institut für Geologie, University of Bern, Baltzerstrasse 1+3 CH-3012 Bern

In the framework of the SeismoTeCH project, which aims at advancing our understanding of seismotectonic processes in Switzerland, seismic velocity models of the Central-Alpine crust are improved and extended on different scales by various tomographic methods. In this study, we present a first 3-D attenuation model of the upper crust. The 3-D inversions derive the quality factor \( Q \) (1/attenuation) using path attenuation \( t^* \) observations for 4192 distributed earthquakes recorded on permanent and temporary stations, including both velocity and acceleration records for the period 2002-2019. The preliminary Qs and Qp results show large-scale features in the upper crust, which are consistent with the recently improved high-resolution velocity models and serve to refine the interpretations of crustal structures from Vp and Vp/Vs. For example, the foreland region of southern Germany and northern Switzerland show a low Q crustal block bounded by high Q regions. This markedly correlates with the overlying surface geology, where low Q areas coincide with the Molasse Basin, and high Q regions outline the geological boundary between the Molasse and the Mesozoic sediments towards north and the Alpine front to the south. At depths ranging between 2 - 6.5 km, low Q is imaged along the Valais where the presently seismically most active fault zones are located. As the attenuation of fractured areas is enhanced by fluids, low Q values may relate here to distributed microfractures that produce greater fracture connectivity and permeability in a relatively higher strain-rate zone. On the other hand, high Q are found in the Black Forest Massif and in the external Aar Massif which is consistent with crystalline basement rocks. In combination with recently developed Vp and Vs velocity models, the 3-D attenuation models of the uppermost crust will provide crucial input for next generation seismic hazard models in Switzerland, allowing for a more realistic prediction of earthquake related ground motions.
P 7.3
Using the Swiss database of potential earthquake evidence to develop paleo-earthquake scenarios

Katrina Kremer*,**, Remo Grolimund*, Donat Fäh*

*Swiss Seismological Service, ETH Zurich, Sonneggstrasse 2, 8092 Zurich (katrina.kremer@sed.ethz.ch)
** Institute of Geological Sciences and Oeschger Centre for Climate Change Research, University of Bern, 3012 Bern

Information on prehistoric earthquakes are needed to extend the instrumental and historical earthquake catalogues for large damaging events (Magnitude Mw > 6). This allows to better constrain return periods of such very rare events, which is of interest in particular for areas of moderate seismicity such as Switzerland. Moreover, paleo-seismological methods might provide information to better constrain the maximum magnitudes to be expected for a probabilistic seismic hazard assessment.

Traces of prehistoric earthquakes can be found in the geological record. These are traces from primary effects such as fault ruptures or from secondary effects such as landslides, sediment liquefaction, tsunami deposits and broken speleothems in caves. A reliable compilation of dated traces can be used to reconstruct paleo-earthquakes.

Therefore, a database of potential paleo-seismic evidence in Switzerland has been compiled including information from limnogeology, sedimentology, geomorphology, archaeology and speleology (Kremer et al., 2020). At present, the database includes ~700 datapoints covering the period of the last 20,000 years. These datapoints have different levels of dating quality and uncertainty, as well as source reliability. These differences have been taken into account and categorized. Our database allows to define clusters of increased occurrence of such traces in time and space, and to determine periods of potentially enhanced earthquake activity. However, not yet included in our analysis are the locations and magnitudes of these potential earthquakes that could have been responsible to generate the traces found. Thus, a further step is to analyse possible prehistoric earthquakes through scenario modelling, and to assess epicenter locations and magnitudes with their uncertainties. In this contribution, we propose a workflow that will allow us to compute paleo-earthquake scenarios based on the existing potential paleo-seismic evidence database for Switzerland.

REFERENCE
P 7.4
Designing a probabilistic workflow for the assessment of the earthquake-triggered landslide-tsunami hazard along the shores of perialpine lakes

Michael Strupler*, Flavio S. Anselmetti**, Paola Bacigaluppi***, Robert M. Boes***, Katrina Kremer*/**, David F. Vetsch***, Stefan Wiemer*

*Schweizerischer Erdbebendienst (SED), ETH Zürich, Sonneggstrasse 5, CH-8092 Zürich (michael.strupler@sed.ethz.ch)
** Institut für Geologie und Oeschger-Zentrum für Klimaforschung, Universität Bern, Baltzerstrasse 1 + 3, CH-3012 Bern
***Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW), ETH Zürich, Hönggerbergring 26, CH-8093 Zürich

It has been documented that since deglaciation, landslide-tsunamis have occurred on multiple Swiss perialpine lakes (e.g. Cysat 1969; Bussmann & Anselmetti 2010; Kremer et al. 2012). However, on most lakes, the landslide-tsunami hazard is not well understood, due to sparse information from historical events on the hazard metrics (e.g. flow depth, flow velocity, run-up and inundation). In the absence of detailed historical data, models that simulate the hazard can be useful. The main steps in the assessment of tsunamis comprise the modelling of (1) the tsunami generation, (2) the tsunami propagation, and (3) the tsunami run-up and inundation. Each of these steps of the process chain adds uncertainty to the expected results. To consider the effects of the many uncertainties involved, a probabilistic tsunami hazard assessment (PTHA) is necessary. Due to the complexity of the process chain and related computational limitations, many existing studies focus on only one of these main steps of the tsunami assessment.

Here we present a first design of a workflow for the earthquake-triggered landslide-PTHA on perialpine lakes, that includes uncertainty quantification for each part of the process chain. Properties of past and hypothetical landslides are sampled based on available information from previous studies with “R” software, and numerical modelling of the tsunami wave is conducted using BASEMENT (Vetsch et al. 2019). The final outputs of the workflow will be distributions of flow depths, flow velocities, and the inundation area.

REFERENCES
Bussmann, F., & Anselmetti, F.S., 2010: Rossberg landslide history and flood chronology as recorded in Lake Lauerz sediments (Central Switzerland). Swiss J. Geosci. 103, 43–59