Seismic Response of Squat Walls Founded on Gravel Cushions

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ABSTRACT
In the South Iceland Seismic Zone (SISZ) earthquakes of magnitude up to seven can be expected. Recent well-recorded earthquakes in this region have caused significant damage to buildings. Many buildings in SISZ are 1-3 story reinforced concrete buildings founded on shallow foundations laid on gravel cushion. Interaction of shear walls with the relatively flexible foundation are believed to result in partial isolation of the superstructure from the effects of ground shaking. The beneficial effect of such interaction seems evident from field observations. For example, buildings in the village Hveragerði, located only 3-5 km from the fault rupture, have experienced peak ground acceleration close to 90% of gravitational acceleration and performed very well during the May 2008 Ölfus Earthquake with a recorded moment magnitude of 6.3. Even at a peak horizontal ground acceleration level more than twice the current design specification, a majority of the residential buildings escaped collapse. Structural yielding was not significant, possibly due to reduced base shear demand and energy dissipation at the foundation. This contribution presents the preliminary results of an ongoing study on the effects of flexible foundation on seismic response of squat shear walls.

Keywords: Soil Foundation Structure Interaction (SFSI), Near-fault ground motions, Squat Wall

1 INTRODUCTION

Soil-Foundation-Structure-Interaction (SFSI) plays an important role with the study of structures supported on flexible soils. The dynamic interaction between the soil, foundation, and structure during an earthquake can significantly impact the response of the system by altering the natural period and damping of the fundamental mode. Dynamic SFSI problems merit a direct time domain approach, in which non-linear effects are considered. In the case of strong earthquakes, the conventional linear elastic soil structure interaction (SSI) process lacks consideration of the nonlinear geometrical and deformation effects present at the soil-foundation interface. Structural assessments following the Ölfus Earthquake in 2008 concluded that, given the intensity of the earthquake, some of the buildings performed better than would have been expected. Dissipation of seismic energy in the form of foundation uplift and plastic soil deformation likely served to reduce the forces transmitted to the structures.

Ground motion characteristics in Iceland are relatively well understood through monitoring and modelling activities (Halldórsson and Sigbjörnsson 2009). Construction methods in the region including foundation materials are also well documented. With the availability of high-quality data from a realistic practical setting, the Icelandic landscape provides a natural laboratory for the study of Soil Foundation Structure Interaction (SFSI) systems.

1.1 Seismotectonics of Iceland

The North-American tectonic plate and the Eurasian tectonic plate meet at the diverging Mid-Atlantic Ridge which is currently expanding the Atlantic Ocean in the northern hemisphere at an average rate of 2 centimeters per year as shown in Figure 1.

The plate boundary and relative plate motion can be determined by the observed focal mechanisms of earthquakes in seismic zones and from GPS measurements. One segment of the Mid-Atlantic Ridge called the Reykjanes Ridge traverses Iceland where it extends above sea level. The onshore part of the plate boundary crosses the island from southwest to north, and contains two transform zones, the South Iceland Seismic Zone, SISZ, and the Tjörnes Fracture Zone, TFZ. Seismic activity occurs everywhere on the plate boundary but these two main seismic zones are regions where the earthquake hazard is the highest and large earthquakes have the greatest potential for occurrence (Fig. 1).

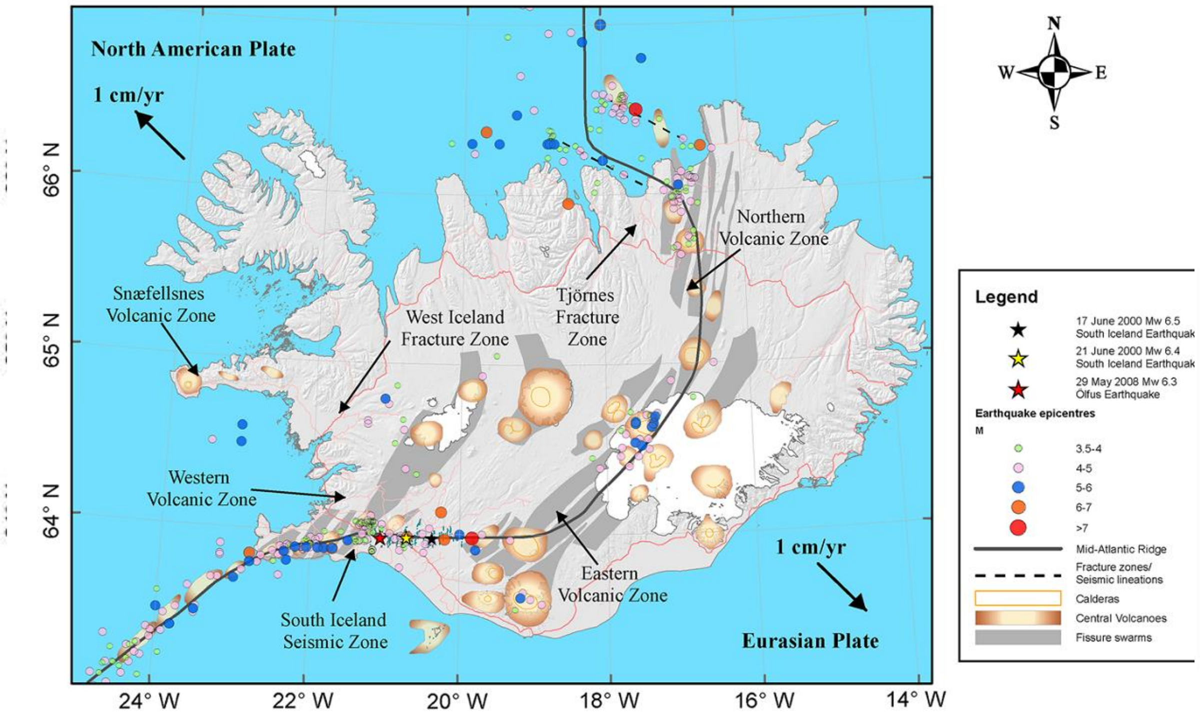

Figure 1: Seismotectonics of Iceland showing the Mid-Atlantic Ridge, the major rifts and fracture zones (D'Amico 2015)

1.2 SISZ

Since 1896, the most destructive earthquakes have occurred in the SISZ, a region with a high population density relative to the rest of the country and several critical infrastructures including hydropower plants, geothermal power plants, and transportation networks. In 1896, six earthquakes larger than Magnitude (M) 6.0 occurred over a two-week period within 50 km (Einarsson et al. 1981; Stefánsson and Halldórsson 1988). Since then an M7.0 occurred in the easternmost part of the SISZ in 1912, a M6.0 occurred in Vatnafjoll in 1987, two Mw6.5 occurred in south Iceland in 2000, and an Mw6.3 occurred in the Ölfusá district in 2008 (Einarsson 1991; Halldórsson and Sigbjörnsson 2009; Halldórsson et al. 2007; Pagli et al. 2003; Sigbjörnsson et al. 2009; Vogfjord 2003). Earthquakes up to magnitude 7 can be expected in SISZ (Halldórsson 1992).

The SISZ spans E-W roughly 80 km in length and about 25 km wide. A maximum fault length of up to 18 km has been observed with horizontal and vertical offsets up to 2 m and 0.5 m respectively. During the 17 June and 21 June 2000 earthquakes, source faults were distanced at approximately 15 km (Khodayar et. al 2010).

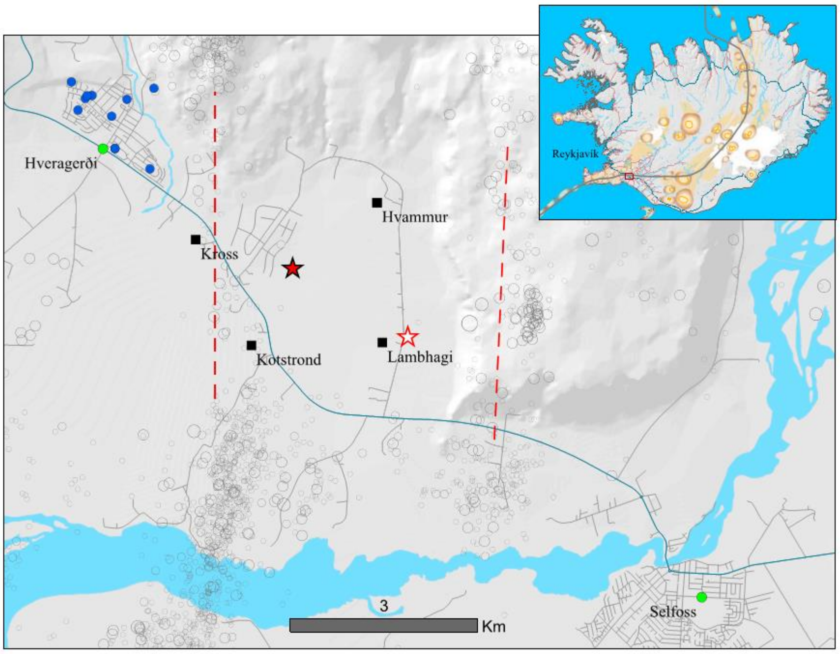

Figure 2. A map of South Iceland showing the epicentral area of the 15:45 UTC 29 May 2008 Ölfus Earthquake, the approximate locations of the two causative faults are delineated by the red dashed lines, the Ingólfsfjall fault to the east and the Kross Fault to the west. The solid red star marks the macroseismic epicenter and the hollow star marks the epicenter estimated from strong ground motion data (Sigbjörnsson et al. 2009). The blue circles in Hveragerði are locations of ICEARRAY recording stations. The grey open circles are epicenters of earthquakes recorded from 23 May to 31 June 2008. The top right inset picture shows Iceland with the mid-Atlantic ridge (grey curve) and the study area is marked by a red rectangle (Rupakhety 2015).

The Ölfus Earthquake, a seismic event of recorded moment magnitude 6.3, occurred on the 29th of May 2008 at 15:45 UTC. The macroseismic epicenter originated beneath Ingólfsfjall roughly 6-7 km east of the town Hveragerði between the towns of Selfoss and Hveragerði. The earthquake occurred almost simultaneously on two parallel, nearly vertical, north–south oriented faults with right-lateral strike-slip mechanism. The faults and the macroseismic epicenters are shown on Figure 2. The earthquake motions were recorded by the Icelandic Strong-motion Network and ICEARRAY network, a dense array in the village of Hveragerði (Halldórsson and Sigbjörnsson, 2009). The Ölfus Earthquake ground motion can be characterized by short duration, high intensity movements.

The Earthquake Engineering Research Centre (EERC) of University of Iceland carried out a detailed survey of damage to the buildings in Hveragerði. A majority of the buildings were built before earthquake design codes were established and enforced. Many of the buildings were damaged in the earthquake but there were almost no reports of collapse. The average damage on residential buildings was about 5% of their insured value, remarkably small given the intensity of the ground motion (Rupakhety and Sigbjörnsson, 2014). This is in agreement with other studies of damage of low-rise buildings in the area after the 2008 Ölfus Earthquake (Bessason et al. 2012) Unreinforced masonry buildings suffered the most damage. Damage to concrete as well as timber buildings was mostly limited to non-structural elements such as wall and floor tiles, paints, ceilings, doors and windows, etc. The earthquake excitations on the buildings far exceeded the codified design loading but a majority of buildings performed well and withstood the high accelerations. Most buildings in Hveragerði are one to two stories, include shear wall lateral load resisting systems, made of concrete, symmetric, and regular in both plan and elevation (Rupakhety et al. 2015; Bessason et al. 2014).

Several houses had noticeable foundation deformation where permanent tilt, extensive damage to floors, and cracking in foundation walls. In Iceland, structures are often founded on gravel fill atop shallow bedrock. The gravel cushion deforms and serves as a damping mechanism for the dissipation of seismic energy. These type of foundations can reduce the base shear loads or inertial forces transmitted to the structure. This effect may have helped the buildings to withstand the event practically unscathed. For a gravel cushion, the dynamic behavior will have strong non-linear characteristics and is more likely to interact with the structure. The dynamic response of the structure as a whole depends on the dynamic characteristics of the foundation and thus the interaction of the system must be accounted for. An example time series from an accelerometer installed at the Hveragerði Retirement House is provided in Figure 3:

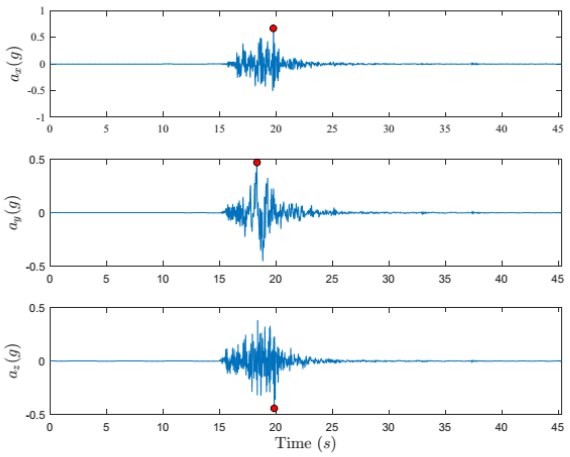

Figure 3: Corrected accelerometer readings from the Ölfus Earthquake that occurred on 29 May 2008. Maximum ground accelerations recorded at the site in the East-West, North-South, and vertical directions were 0.66g, 0.47g, and 0.44g, respectively. These readings were taken from the Hveragerði Retirement House station at an epicentral distance of 9 kilometres (Fig. 2).

2 SOIL-FOUNDATION-STRUCTURE INTERACTION

2.1 Introduction

In most practical engineering applications, depending on the soil conditions and the structural type, the foundations are partially or totally embedded in the ground and the effects of the surrounding soil greatly alter their static and dynamic response. Many buildings in SISZ are 1-3 story reinforced concrete buildings founded on shallow foundations wherein the shear walls are classified as squat walls and energy dissipation is dominated by structural yielding, sliding, and bearing capacity mechanisms.

As opposed to a fixed base structure subjected to free-field ground motion, the presence of a structure founded on compliant substrate will modify the free-field motion and the interaction between subsystems will modify the expected response.

Studies have shown that allowing significant sliding, uplifting, and even mobilization of bearing capacity failure mechanisms can result in a more distributed inelastic phenomenon through the structure and foundation, and yet acceptable permanent translational and rotational deformations. However, when unintended and uncontrolled, these mechanisms can produce adverse effects, such as, excessive permanent deformation resulting in excessive damage to the foundation, excessive cracking on the shear walls, non-structural damage, etc. Thus there is a need to understand the energy dissipation contributions of the different mechanisms in squat walls founded on soft/medium soil, and to quantify how yielding can be apportioned to the different mechanisms in the structure and the foundation to obtain a good design solution.

2.2 Squat Walls

For structural walls, the behavior of the lateral force resisting system during a seismic event will vary with the aspect ratio and wall layout. Walls with low aspect ratios (≤2.0) are known as squat walls. Squat walls typically have a height to length ratio smaller than 0.5 and have a very high stiffness and strength capacity. Lateral forces are resisted through a combination of the strength of the concrete and distributed horizontal and vertical reinforcement, forming a diagonal strut mechanism. The three major failure modes of squat walls are diagonal tension, diagonal compression, and sliding shear

(Gulec 2005). Squat walls can experience a complex interaction of flexure, shear, and sliding shear failure modes.

For squat walls with very small aspect ratios (aspect ratios ≤2.0), they tend to have a high inherent shear strength and low ductility demands. The ductile mechanism of flexural yielding is limited by the geometry of squat walls; thus they tend to fail in either flexure shear or shear sliding.

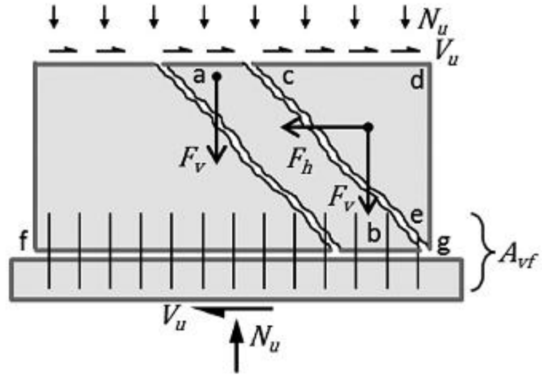

Figure 4: Shear yielding and sliding in a squat wall (Moehle 2011).

Shear yielding occurs when the wall develops inclined cracks, as shown in Figure 4. Shear sliding typically occurs at the structure-foundation interface. Shear failure modes are regarded as undesirable brittle failure modes since rapid loss of strength and stiffness occurs after very little deformation (Whyte 2013). With such quasi-brittle responses as the main indication of deformation, they occur suddenly, and are not preceded by significant yielding, either in flexure or in tension induced by shear.

Figure 5: Typical squat wall structure in the SISZ.

Squat walls are relatively rigid structures, their natural frequency of vibration are in the sensitive range to peak value ground motions, most of which tend to fall in the 0.2 to 0.5 second range. A typical 1 story reinforced concrete structure has a natural period below 0.2 seconds if assumed to be founded on rock. Squat walls have an insufficient amount of ductility to dissipate seismic energy. When founded on soft foundation, the vibration frequency of the structure is reduced. Given the rigidity of the structure and the flexibility of the foundation, the foundation is expected to deform while the squat wall remains elastic. If damage occurs in the structure, it will likely be either flexural or shear cracks in the plane of the wall.

Figure 6: Damaged squat wall in Hveragerði after the 2000 earthquake with visible shear crack.

Stiff structures tend to develop large deformation ductility demands if loaded beyond the elastic range. In order to reduce the demand on the shear walls, allowance of inelastic deformation of the foundation seems to be favorable. Such deformation needs however to be limited so as to avoid excessive damage to the foundation permanent displacement and tilting of buildings.

2.3 Soil Profile and Foundation

At many sites in Hveragerði, there is a thin organic soil layer up to 3 meters in depth. During construction, it is common procedure to excavate and remove this soil and to either build directly on rock or to put the foundation on a 1–2 m thick compacted gravel refill, drained conditions can be assumed with no volumetric changes under shear. At some other locations in South Iceland there are thick sediments of stiff sand and gravel sites where some soil interaction can be expected (Bessason and Erlingsson 2011). With the squat walls embedded below grade, the lateral earth pressure from the surrounding soil prevents sliding of the wall relative to the foundation.

2.4 Preliminary Modelling

An equivalent linear system model of the shear walls, foundation, and soil can be established for numerical simulation of seismic response. A number of assumptions were made to formulate a discrete model representative of a simple 1 story structure, typical of those found in the SISZ. To investigate the potential impact of SFSI in the response of a typical construct, a crude model will be introduced.

The first mechanism of focus is the uplifting of the foundation, which causes a shift in the natural period of the system and results in additional energy dissipation due to the rocking of the foundation.

The conventional soil-structure interaction methodology replaces the actual structure by an equivalent simple oscillator supported on a set of frequency-dependent springs and dashpots which represent the stiffness and damping of the underlying medium.

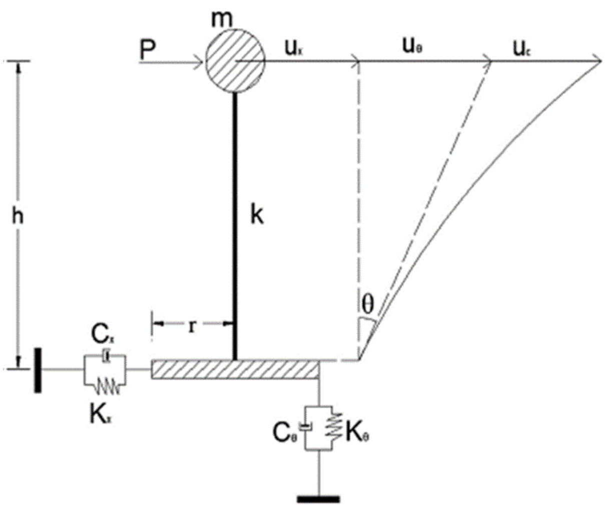

Figure 7: Maravas (2008) soil-structure system deflection diagram.

The structure shall be represented as an SDOF system, which can be an idealization of a one story structure, height h, with a lumped mass, m, concentrated at the story level, damping ratio ζ, which may be viscous (linearly proportional to frequency) or linearly hysteretic (independent of frequency), and stiffness, k. The stiffness of the structure can be represented by a massless column or frame which has an effective height h derived from the fixed-base natural period of the structure. The foundation is assumed to be a circular shallow raft foundation of radius r. The shear wall structure is assumed to have a gravel foundation substrate immediately beneath the foundation. The compliance of the substrate beneath the mat foundation is included at the supports with two frequency-dependent springs, K_x and K_θ, representing stiffness in two degrees of freedom for translational (swaying) and rocking oscillations, respectively. Damping is represented by C_x and C_θ, a pair of dashpots representing energy dissipation due to hysteresis and unbounded wave radiation (Veletsos & Nair 1974). By representing the structure, foundation, and underlying soil in this manner, equivalent natural properties, such as $\tilde{K}, \tilde{T},$ and $\tilde{\zeta}$ of the linear Soil-Foundation-Structure (SFS) system, can be determined.

During a seismic excitation, the SFS model depicted in Figure 7 will undergo three different modes of vibration: translation motion of the lumped-structure mass, translational motion of the lumped-foundation mass, and rotational motion of the system about the foundation. The total horizontal deflection of the system can be decomposed into a summation of independent deflections:

$$u_{total} = u_x + u_\theta h + u_c \qquad (1)$$

Where u_{total} is the total displacement of the lumped structural mass relative to the ground, $u_x(\omega)$ is the horizontal displacement of the foundation, $u_\theta(\omega)$ is the foundation rotation, $u_c(\omega)$ is the flexural deformation of the column supporting the structural mass, and $\omega\ \left({rad}/{s}\right)$ is the cyclic excitation frequency. Generally, the impedance functions are dependent on the geometry of the foundation, the frequency of excitation, and the characteristics of the underlying soil. Maravas (2006), Luco and Westman (1971), and Veletsos and Wei (1971) suggest the dynamic impedance of the system is complex valued and frequency dependent. The dynamic impedance for the jth degree of freedom of the SFS system, can be expressed as follows:

$$K_j^*(\omega) \equiv \mathrm{k}_j\left(1 + 2\mathrm{i}\zeta_j\right) \tag{2}$$

Where k_j is the static stiffness and real component of the impedance and ζ_j is the energy loss coefficient.

From equation (1), the impedances associated with each degree of freedom are assumed to act in parallel and can be expressed through a summation rule yielding the following expression for the total dynamic impedance of the SFS system:

$$\frac{1}{\widetilde{K}^*} = \frac{1}{{K_x}^*} + \frac{1}{{K_\theta}^*}\left(\frac{h}{r}\right)^2 + \frac{1}{{K_s}^*} \tag{3}$$

Where $\widetilde{K}^*$ is the overall dynamic impedance of the SFS system, ${K_x}^*$ is the complex stiffness associated with the translational oscillations, ${K_\theta}^*$ is associated with the rocking oscillations, ${K_s}^*$ is associated with the structure, and $^h/_r$ is the slenderness ratio.

Veletsos et al (1977) presented a series of dimensionless parameters to relate the properties of the structure-soil system to an equivalent fixed base structure. Maravas (2006) expanded upon the procedure and established analytical expressions for the linear damping and fundamental natural period of the SFS as an iterative method involving the aforementioned frequency-dependent impedances and system geometry. Simplified approaches such as the one briefly mentioned in this section could be utilized to simulate the mechanisms of the SFS system.

2.5 Near Fault Effects

Since the village of Hveragerði is located only 3-5 km from the fault rupture, the behavior indicative of the peculiar characteristics of near fault ground motions is observed. In the small area covered by the array (spatial dimensions are only ~2 km), there was a large variability as indicated by the range of PGA as well as the frequency-content of ground-motion (Halldórsson and Sigbjörnsson 2009).

The records also showed forward-directivity effects, i.e. a near fault focusing of seismic energy in the fault-normal direction, evidenced by the dominant long-period pulses in the velocity time series (see Rupakhety et al. 2011).

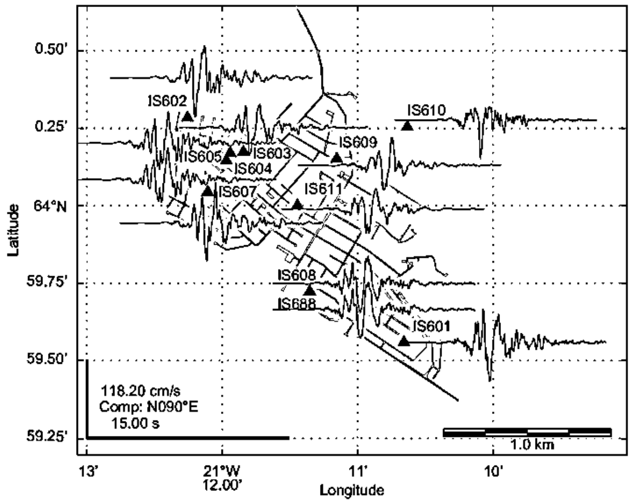

Figure 8: East-west components of the strong-motion velocity time series recorded by the ICEARRAY during the Ölfus Earthquake on 29 May 2008(Halldórsson and Sigbjörnsson 2009).

Near-fault ground motions, specifically the ground velocity and displacement, have a pulse-like nature which seems to reduce the beneficial effects of soil-structure interaction. The ground motions are characterized by a few cycles of intense shaking, and therefore energy dissipation due to hysteresis at the foundation is not as efficient as in the case of ground motion with many cycles of shaking. The response seems to be controlled by the dominant velocity pulses contained in the ground motion (a strong pulse in the long period range). Base-isolated buildings could experience severe displacement demands due to displacement pulses within the near-fault ground motion if designed according to standard provisions (Hall et al. 1995).

This was the case for the base isolated Óseyrarbrú bridge during the May 2008 Ölfus Earthquake (Jónsson, Bessason and Haflidason, 2010). Rupakhety et al. (2010) conducted a study of near-fault ground motions in detail and the possible impact on engineering structures. If the near-fault pulse is resonated with the structure, this may result in a permanent tilt since excessive demand is experienced by the foundation. If the ground motion was composed of more cycles, then there is potential for more dissipation of seismic energy and recentering mechanisms to restore the system. A time history analysis using a large set of near-fault ground motions needs to be performed to investigate the effects of foundation flexibility.

2.6 Attenuation and Amplification Effects Due to Soil Profile

Geologically, Iceland is characterized by basaltic lavas, as well as tuff layers, often with intermediate layers of sediments or alluvium. The soil composition could potentially impact the ground motion as in the case of the Ölfus Earthquake, where the causative faults were located at a relatively shallow depth but were not visible on the surface (Sigbjörnsson et al. 2009). The characteristics of the soil can greatly influence the nature of shaking at the ground surface during an earthquake. The sediment layers overlaying the bedrock, can act as "filters" to seismic waves travelling to the surface by attenuating motions at certain frequencies and amplifying them at others. The geological profile in the town of Hveragerði is fairly uniform (see geological map of the area in Sæmundsson and Kristinsson 2005) but this would be an important consideration for sites outside of Hveragerði.

3 CONCLUSION

From field observations, the beneficial effects of considering flexible foundations on seismic performance of buildings seems evident—for example, buildings in Hveragerði during the May 2008 Ölfus Earthquake performed very well The flexible foundation acts like a 'fuse', a 'natural isolation mechanism', wherein yielding of foundation limits the seismic forces transmitted to the superstructure.

Building design codes are overly simplified in that the assumptions cannot capture the non-linear dynamic interaction between the structure-foundation-soil system during seismic events. A full-scale validation of structural response through recorded earthquake excitations is important. Eurocode 8 allows full scale earthquake testing using a computational or scaled test model in addition to the prescribed methods provided that the design fulfils the code requirements.

3.1 Next Steps

- Efficient and reliable mechanical modelling of SFSI systems that are suitable for the Icelandic environment will be investigated, presented, and verified with experimental data.
- Through case studies the 'natural isolation mechanism' which can act like a 'fuse' and under what circumstances the deformation of the foundation becomes excessive and uncontrolled will be determined.
- The objective is to propose potential simplifications in modelling for everyday design office use while still capturing the dynamic characteristics of the system.
- Numerical simulations using the mechanical model will be critically analyzed to identify trends, to understand the most important effects, and to suggest possible mitigation strategies.
- The results will shed light on factors such as relative distribution of yielding mechanisms in the structure and the soil, and the scenarios that result in favorable and unfavorable failure mechanisms.
- This study will also seek to quantify the effects of different parameters of the soil, the structure, and ground motion, on the overall response of the structure.

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