Dam and Foundation Reponses to the 2016 M_W 7.8 Kaikōura Earthquake in New Zealand

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Dam Safety Intelligence.

The M_W 7.8 Kaikōura earthquake on 14 November 2016, ruptured over 20 faults during the initial shaking, which lasted nearly two minutes. A complex series of fault ruptures propagated northeast for nearly 180 km from the initial rupture location. Instrumentation from dams across New Zealand shows that whilst most dams did not suffer physical damage, piezometric responses were measured in dams and their foundations. Earthquake related changes in seepage regimes are not unusual and depend on the characteristics of the ground motions, and site specific characteristics that influence how a dam and its foundation respond to ground motions. The ability to measure a piezometric response in a dam or foundation is heavily influenced by the instrumentation network and method of monitoring. Data collected during events such as the Kaikōura earthquake provides valuable information for both characterising performance of a dam during the event, and assisting future analysis such as failure mode assessments. Careful consideration must be given to the scope of installed instrumentation and the frequency of monitoring in order to provide these benefits, and the robustness of the system to ensure it adequately survives the event.

Keywords: *Kaikōura earthquake, dam foundation response, ground motion amplification, dam monitoring.*

Introduction

On 14 November 2016, a Moment Magnitude (M_W) 7.8 earthquake occurred in the upper part of the South Island of New Zealand and was felt across the majority of the country. A complex series of fault ruptures, in which over 20 faults were ruptured, propagated northeast for nearly 180 km from the initial rupture location, lasting almost two minutes. The highest confirmed peak ground accelerations were ~1.25 g vertical and horizontal nearly 130 km northeast of the originating epicentre. Damage was widespread and two lives were lost. New Zealand's portfolio of dams generally performed well; no dams failed. However, a number of irrigation and farm dams in the north of the South Island were damaged and several hydropower stations tripped offline due to ground motions exceeding the thresholds of their safety devices. Instrumentation installed at many dams has shown that while most dams suffered no physical damage, many have shown a piezometric response to ground motions.

This paper presents a summary of measured piezometric dam responses in a number or locations across New Zealand following the Kaikōura earthquake and discussion of factors that influence ground motions and a dam's response to given ground motions.

New Zealand's tectonic and seismic setting

New Zealand's tectonic and seismic setting is well researched and documented; for example recently in Kaiser et al (2017) and Hamling et al (2017). A description derived from these publications is included as a summary here.

New Zealand's tectonic setting is largely defined by two subduction systems linked by an area of oblique continental convergence, refer Figure 1. In the North Island, the Pacific Plate subducts westward beneath the Australian Plate along the Hikurangi subduction margin. Relative plate motion is approximately 39 – 48 mm/year. The northern part of the South Island is dominated by oblique continental convergence, primarily along the transpressional plate boundary referred to as the Alpine Fault. The area between the Hikurangi subduction margin and the Alpine Fault is referred to as the Marlborough Fault System where slip rates average up to 25 mm/year. In the southern parts of the South Island, the Australian Plate subducts eastward beneath the Pacific Plate; i.e. the opposite to the North Island.

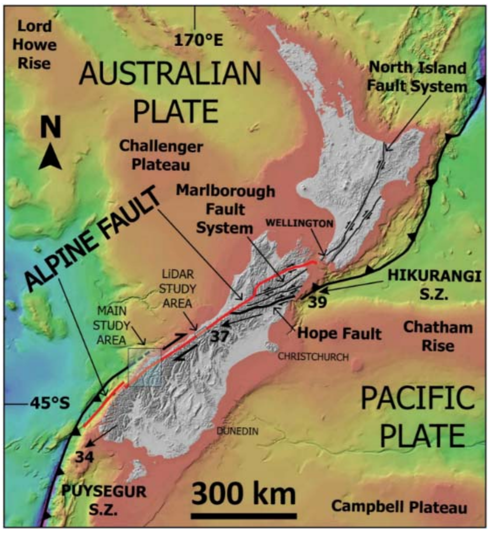

Figure 1: New Zealand tectonics. Subduction zone is abbreviated as S.Z. Reproduced from Barth 2012.

New Zealand is a seismically active country and there have been 30 notable shallow earthquakes, generally less than 30 km deep and greater than M_W 6.0, since 1848, the largest being a M_W 8.2 near the south end of the North Island in 1854 (GNS 2016). The M_W 7.8 Kaikōura earthquake is the second largest in New Zealand on record; there have been three others of this magnitude in 1929, 1931, and 2009, and the largest recorded was a M_W 8.2 in 1855.

November 2016 Kaikōura earthquake

Summary of events

A M_W 7.8 earthquake occurred in the upper South Island of New Zealand at 12:03 a.m. local time on 14 November 2016 at a depth of 15 km (GeoNet 2016). The epicentre was situated near the small rural South Island town of Waiau, approximately 100 km north of Christchurch, and approximately 60 km southwest of Kaikōura. The earthquake has subsequently been referred to as the Kaikōura earthquake. As of 20 June 2017, over 17,000 earthquakes have been recorded since the initial M_W 7.8 event, of which 549 were M_W 4-4.9, 61 were M_W 5-5.9 and 5 have been M_W 6.0 or greater (GeoNet 2017a).

Fault ruptures and propagation

The Kaikōura earthquake involved a complex sequence of fault ruptures that lasted almost 2 minutes. At least 21 faults have since been found to have ruptured during that event. 12 - 14 of these faults were the primary contributors to the overall energy released while the others were regarded as superficial (RNZ 2017). Fault displacements greater than a metre occurred on at least 13 faults (Kaiser et al 2017). The greatest surface displacements measured to date are up to 12 m horizontal on the Kekerengu Fault, and up to 6 m vertical on the Papatea Fault (Kaiser et al 2017). Figures 2 and 3 show examples of surface displacements generated by the Kaikōura earthquake. Most of the identified fault ruptures were along known faults; however, some were previously unidentified. The total length of fault rupture was around 180 km which accounts for the long duration of shaking experienced during the earthquake. Kaiser et al (2017) reported that while seismic modelling (Stirling et al 2010) provided the possibility of a combined rupture of dominant faults in this region during a large event, the Kaikōura earthquake led to rupture of a much larger number of faults with a greater amount of energy released than anticipated.

Preliminary analysis (Kaiser et al 2017) indicates at least four stages of rupture were identified, with three distinct northeastward-propagating phases of energy release as illustrated in Figure 4.

Figure 2: Vertical surface displacement along Leader Fault. Photo courtesy of Kate Pedley.

Figure 3: Vertical and horizontal surface displacement along Kekerengu Fault. Photo courtesy of Tim Little.

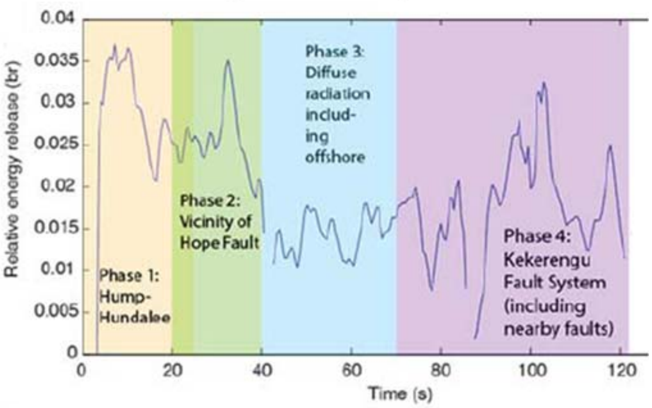

Figure 4: Four phases of fault rupture and three peaks in energy release. Reproduced from Kaiser et al 2017.

Felt intensities and ground motions

Distribution across New Zealand

Felt reports from the public extended almost the full length of New Zealand, a span of approximately 1200 km. New Zealand's geological hazard monitoring centre, GeoNet, has a network of ~200 weak motion sensors, ~260 strong motion seismometers, and ~200 continuous Global Navigation Satellite System (GNSS) (Kaiser et al 2017). Datasets collected by GeoNet are available to the public and have been used in this paper to provide an overview of ground motions across New Zealand.

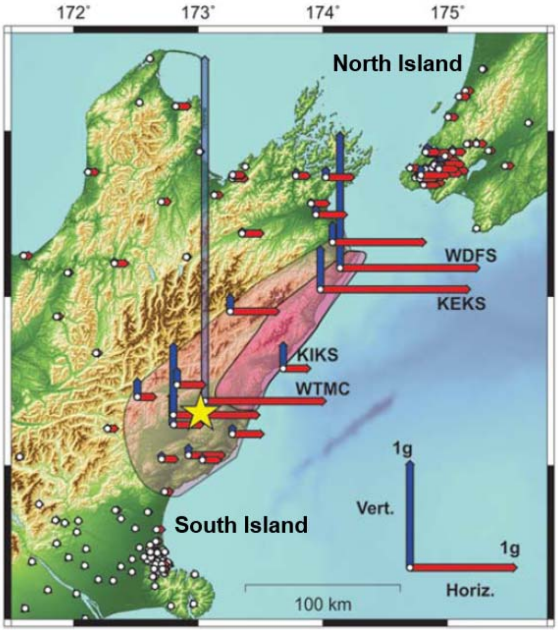

Figure 5: Peak ground accelerations (PGAs) measured at GeoNet monitoring stations during the Kaikōura earthquake. Epicentre shown as yellow star. Note PGAs at top of South Island and at bottom of north island are much larger than those at locations south of the epicentre. Extremely large vertical PGA near epicentre (transparent blue) under investigation to confirm if real. Pink shaded areas represent extent of mapped landslides with majority in the darker shaded area. Original image reproduced from Kaiser et al 2017.

The northwards propagation of fault ruptures and the multiple phases of energy release are reflected in the distribution of ground motions across the country. Horizontal and vertical PGAs greater than 1 g were recorded near the epicentre, and also around 130 km northeast near the top end of the fault rupture where vertical and horizontal PGAs were ~1.25 g. With the exception of an extremely high vertical PGA of over 3 g recorded near the epicentre, which is under investigation to its validity, these were the highest PGAs recorded. Figure 5 illustrates the PGA distribution across the top of the South Island and bottom of the North Island. There are clear similarities between the PGA distributions and the current understanding of the propagation of fault ruptures and phases of energy release summarised in Section "Fault ruptures and propagation".

Dam site ground motions

While some large dams have accelerometers installed, ground motions measured at specific dam sites were not available for this review. However, this data may become available at a later date and will provide additional insight into the observed responses as discussed in this paper. Ground motions from selected GeoNet monitoring locations have be used to indicate the scale of ground motions where data is available within ~30 km of a the dam site and are included in Table 1 alongside the recorded piezometric responses.

Comparison of ground motions and discussion of influencing factors

There is a large amount of research into factors that influence how seismic waves travel through the ground and the characteristics of ground motions for a given magnitude seismic event, e.g. topographic amplification, soil effects, and directivity. These are some of the more commonly discussed factors and are summarised below.

Topographic amplification

Topographic amplification is associated with the surface topography e.g. hills/mountains, valleys, cliffs, and potentially complicated subsurface geometries e.g. sedimentary basins, and geological lateral discontinuities such as faults. These features have been shown to significantly affect the intensity, frequency, and duration of ground shaking during earthquakes (Assimaki et al 2013). Topographic amplification of ground accelerations occurs when seismic waves entering the base of a topographic ridge are partially reflected back into the rock mass and diffracted across the free surface where they are focused upwards and constructive interference increases towards the ridge crest, resulting in increased ground accelerations (Meunier et al 2008). Surface topography not only influences the PGA, but can also increase the duration of shaking because of scattered and reflected waves (S-H Lee et al 2009). Topographic amplification ratios typically range from 2 to 10 but spectral amplifications on the order of 20 or more have also been recorded (Assimake et al 2013).

Soil effect

The local geological conditions could modify seismic waves, often referred to in literature as "soil effect". The two most dominant factors are a) the stiffness or rock or soil near the surface, i.e. softer soils or rock will amplify ground motions, and b) the depth of any sediments above solid bedrock, i.e. shaking is amplified where sediments are thicker. A comparison of recorded PGAs across the Wellington region during the Kaikōura earthquake, refer Figure 6, shows higher PGAs on softer grounds such as the Wellington CBD waterfront, which is largely reclaimed land, and the alluvial deposits in Hutt Valley, compared to the harder rock in the hills. Amplification of ground motions also occurs near the edge of sedimentary basins, termed basin-edge effects. Investigation into the cause of partial collapse of two floors at a building in Wellington during the Kaikōura earthquake concluded that amplification of ground motions primarily due to basin-edge effects were one of the determining factors (MBIE 2017).

In addition to the individual topographic and soil effects, literature indicates a coupling between the two which gives rise to a complex phenomenon not captured by superposition of the two factors alone. Assimaki et al (2013) term this the soil-topography coupling effect, and describe it as the trapping of seismic waves in the surficial soil layers, and the subsequent altering of their direction, amplitude, frequency, and duration due to scattering and refraction upon incidence on the irregular ground-surface geometry.

Directivity

Directivity is used to describe the phenomenon in which ground motion in the direction of rupture propagation is greater than in other directions. This will also influence the extent of ground motions in the direction of rupture propagation as well. In the case of the Kaikōura earthquake, greater ground motions were experienced northeast of the epicentre and for a greater distance compared to other directions, e.g. PGAs of up to 0.28 g recorded in Wellington (some 50-60 km northeast of where the fault rupture terminated) are significantly greater than PGAs recorded at a similar distance southwest of where the rupture initiated.

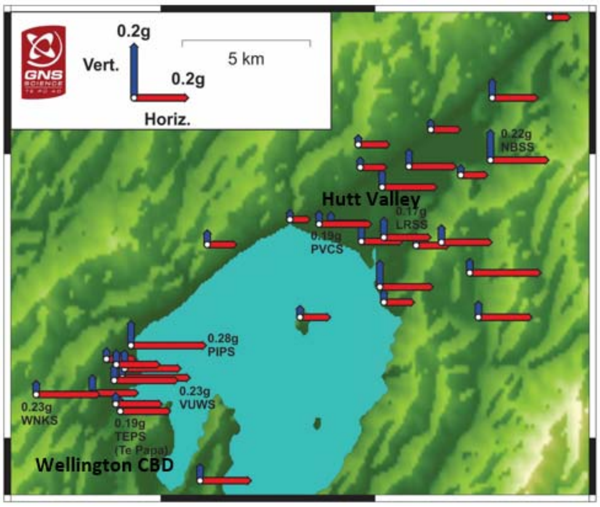

Figure 6: Peak ground accelerations (PGAs) recorded around Wellington region, bottom of North Island. Larger PGAs recorded on softer materials, i.e. reclaimed land around CBD waterfront (bottom left) and alluvial materials of the Hutt Valley (northeast of harbour) compared to those founded on rock on north western fringe of the Hutt Valley. Original image reproduced from GeoNet 2016(b).

Observed response at dams and their foundations

Ability to measure response

The ability to measure a response at a given dam and/or its foundation is influenced by a number of factors. In some cases the response may be severe enough that it can be visually identified, e.g. surface movement or cracking. Following the Kaikōura earthquake, there were reports of visually apparent damage at some embankment dams located in the northern part of the South Island. In cases where damage was not visible or the response was not evident, the possible detection of the response would be primarily influenced by the nature of the seepage regime, as well as by the scope, design, and recording of monitoring instruments available for analysis. This would depend on how the dam is designed, e.g. how seepage is captured and where it discharges. In some cases it is not possible to capture or measure seepage flows through an embankment for example. At some dams, few or no instruments are installed, and basic monitoring of discrete points may not be sufficient to detect a response. In contrast, other dams have extensive networks which may enable detection of changes across the entire structure to be well defined. As well as the location and the extent of instrumentation, the monitoring frequency will also impact on the ability to detect a response to a given event; seismic or otherwise. Reading frequencies typically vary from monthly to hourly and may be manually performed by dam operators (for lower frequencies), or automatically monitored using data acquisition systems and in these cases often remotely monitored using telemetry.

The type of instrumentation will also influence the ability to detect a response. For example differing types of piezometers have different response times, e.g. a vibrating wire piezometer has a much shorter response time to changes in pressure head than a standpipe piezometer. It is therefore possible that temporary responses may not be captured by particular types of instruments.

Responses were detected at dams following the Kaikōura earthquake, both where there have been extensive high frequency monitoring regimes, as well as at dams with a relatively small number of instruments and a relatively low monitoring frequency. That said, it is very likely that additional responses were not captured, even at those dams with extensive instrumentation networks.

Individual dam responses

Instrumentation installed in dams located across New Zealand show varying responses to the Kaikōura earthquake. The largest detected piezometric response was at the Waitakere Dam, located 655 km north of the Kaikōura earthquake epicentre where piezometric pressure drops of up to 4 m were recorded. Piezometric data is plotted in Figures 7 (a) and (b); due to an unrelated communications error, data in the days leading up to the earthquake was not available. Changes in foundation pressures occurred predominantly at concrete dams with rock foundations; however, some responses were also observed at earth dam foundations, which included reduction in earth dam core pressures, and both decreases and increases in abutment pressures. In the 6 months since the earthquake some of the piezometric readings have begun returning to their usual pre-earthquake levels, while others appear to have equilibrated at new normal levels.

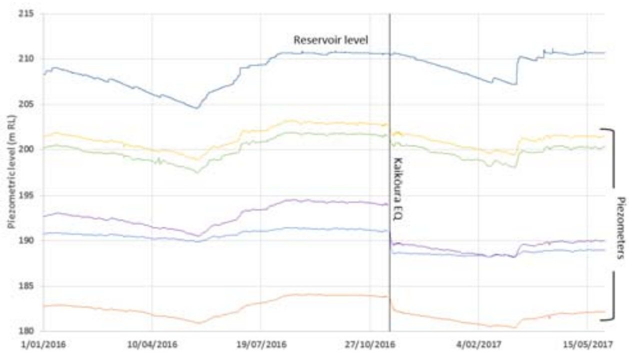

Figure 7a: Response at Waitakere Dam foundation piezometers, large time scale (January 2016 - May 2017) with reservoir level. Vertical line represents Kaikōura earthquake.

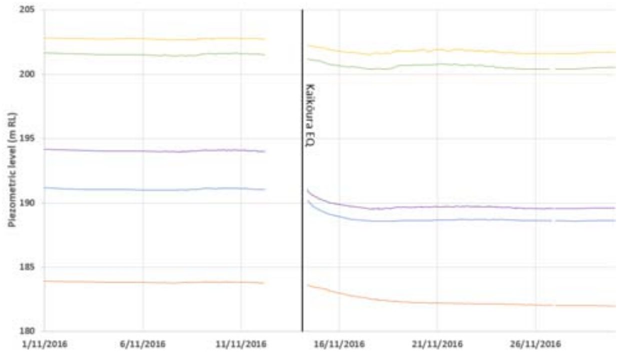

Figure 7b: Response at Waitakere Dam foundation piezometers, small time scale (November 2016). Vertical line represents Kaikōura earthquake.

A summary of responses detected in dams around New Zealand is included in Table 1. This is not an exhaustive record of all detected responses as it is limited to datasets available for analysis. Selected dams where no responses were detected have also been included for comparison with dams in similar regions with measured responses. Where recorded ground motions within ~30 km are available, these have been included as an indicative measure of ground motions in the region; however, this is not intended to reflect likely PGAs at the dam site due to site specific influencing factors which are discussed in this paper.

Table 1: Response at dams and foundations following the Kaikōura earthquake.

Distance from EQ epicentre	PGA at nearby[1] recording site (horizontal / vertical)	Dam and foundation summary	Response summary
South of earthquake Epicentre			
305 km	~0.003*g* / ~0.002*g* Recorded 12 km away	Zoned embankment dam founded on greywacke and overlying alluvial deposits.	None detected
305 km	~0.003*g* / ~0.002*g* Recorded 30 km away	Curved concrete gravity dam founded on greywacke.	0.1 to 0.4 m drop at selected foundation piezometers, and possible disruption of seasonal behaviour.
305 km	~0.003*g* / ~0.002*g* Recorded 25 km away	Zoned embankment dam founded partially on greywacke and argillite, and partially on Tertiary materials including coal seams.	~0.3m increase at piezometer located in coal seam with a history of response to seismic events.
North of earthquake Epicentre			
515 km	~0.026*g* / ~0.013*g* Recorded less than 1 km away	Concrete gravity control structure founded on ignimbrite	None detected
525 km	~0.026*g* / ~0.013*g* Recorded ~ 10 km away	Zoned embankment dam founded on ryolite rib.	Progressive 0.5m drop in water levels in observation wells downstream of dam. Small temperature fluctuations in dam piezometers.

[1] Where GeoNet recorded ground motions are available within ~30 km of the dam.

Distance from EQ epicentre	PGA at nearby[1] recording site (horizontal / vertical)	Dam and foundation summary	Response summary
530 km	~0.005*g* / ~0.004*g* Recorded 15 km away	Zoned embankment dam and concrete gravity dam founded on ignimbrite.	None detected
535 km	~0.005*g* / ~0.004*g* Recorded 18 km away	Concrete arch dam founded on ignimbrite.	Increase in left abutment observation well water levels of up to 2 m. Progressive 2 m drop in right abutment water levels. Increased headrace canal underdrain flows.
540 km	N.A.	Zoned embankment dam founded on ignimbrite.	Progressive 1 m drop in dam piezometers near foundation. Progressive 2 m drop in left abutment water levels.
540 km	N.A.	Zoned embankment dam and concrete gravity dam founded on ryolite, ignimbrite and alluvium.	None detected
540 km	~0.005*g* / ~0.004*g* Recorded 12 km away	Zoned embankment dam founded on ignimbrite and alluvial deposits.	None detected
560 km	~0.005*g* / ~0.004*g* Recorded 27 km away	Concrete arch dam founded on ignimbrite.	Progressive 1.5 - 2 m water drop in selected foundation and underdrain piezometers. Flattening of temperature profile at selected foundation piezometers. Progressive 10 l/m reduction in flow between in foundation drain pressures.
570 km	~0.002*g* / ~0.001*g* Recorded 20 km away	Combination of concrete arch and gravity sections founded on greywacke and argillite.	Water level step-up of 0.5 to 1 m post-earthquake in intake gallery observation wells.
655 km	~0.017*g* / ~0.009*g* Recorded 12 km away	Curved concrete gravity dam founded on weathered agglomerate.	Up to 4 m drop at some foundation piezometers
655 km	~0.017*g* / ~0.009*g* Recorded 12 km away	Homogenous embankment dam with concrete core wall founded on agglomerates and tuffs.	None detected

Factors influencing responses

There are a number of distinct mechanisms to consider for a given dam's response, each with numerous influencing factors. The initial mechanism is energy travelling from the source of the earthquake to a given site for which the sequence of seismic events and fault rupture propagation are the main influencing factors. This is followed by the local site response to the energy received and translated into ground motions, e.g. geology, topography. The response of a dam and its foundation to a set of given ground motions are influenced by a wide range of factors, including dam type and design, foundation type and construction methods. More specifically, and perhaps more significant, are factors such as the characteristics of the foundation, dam, or abutment material including permeability, strength, shape, stresses and any previous response to previous seismic events. There are also complex interactions of the dam-reservoir-foundation system including hydrodynamic effects caused by movement of the reservoir against the dam body and also the influence of the foundation flexibility. In one specific case study, Ayothiraman et al (2008) found that crest displacements for a concrete gravity dam during seismic shaking increased substantially when the foundation is flexible, almost two times compared to a non-flexible foundation, whilst reservoir loading only had a marginal effect in such displacements.

Without specific ground motions and structural acceleration data from individual dams, it is difficult to complete a detailed analysis between different dam and foundation types and it would not be appropriate to complete this analysis based on responses detected in piezometric and seepage monitoring instrumentation alone. However, there are some dams where hypotheses can be made based on the available information. The largest documented responses occurred at the Waitakere Dam, located ~650 km north of the earthquake, and is discussed in further detail below.

Figure 8: Waitakere Dam. Image courtesy of New Zealand Tramper.

As discussed previously in "Comparison of ground motions and discussion of influencing factors", surface topography has been shown to have a significant impact on recorded ground motions with reported topographic amplification ratios of up to 20. The Waitakere Dam is a curved concrete gravity dam with a maximum height of 26 m. The dam is situated on top of a ~110 m near vertical cliff (see Figure 8), and therefore it is plausible that the ground motions experienced by the dam and its foundation were greater than those in the valley below, and potentially much greater than the range of ground motions recorded in the surrounding region. The foundation response recorded, up to a 4 m drop in piezometric pressures, are some or the largest recorded at any dam included in this review despite the relatively large distance, ~650 km, from the Kaikōura earthquake epicentre. Our interpretation of the drop in foundation pressures is that the shaking of the foundation has improved drainage either through the exposed cliff face, or deeper into the foundation. Whilst this behaviour is not yet fully understood, this response is not considered to indicate adverse performance of the dam. Stable pressures relative to lake level since the initial response provides assurance that foundation conditions have not changed any further.

Value of event based dam monitoring

As discussed previously in "Ability to measure response", the extent of instrumentation and type of instrumentation, and the way how it is monitored play critical roles in being able to detect changes in the performance of a dam, its foundation and/or its abutments. Instrumentation is installed to both confirm performance against design intentions as well as to provide an indication of any adverse change in performance or initiation of any potential failure modes, many of which for New Zealand dams are seismically induced. Having a well-designed monitoring programme, which includes instrumentation, is critical to confirm, or otherwise, that performance criteria is met. This does not always have to mean a comprehensive network; responses to the Kaikōura earthquake have been detected at dams with what would be considered a relatively small network. However, the more comprehensive the monitoring network, the more detailed the analysis that can be completed, in particular the ability to understand the extent of response across different areas of the dam and foundation.

As well as the importance of the extent and type of instrumentation, the monitoring method and frequency is also very important. It is not always possible to predict or prepare for significant events such as a large earthquake. Typically this means having appropriate monitoring systems in place all the time. While it is possible to undergo additional inspections and manual data collection, this may not be realistic during significant events due to factors such as restricted access, resourcing, and personal safety. Having telemetry and a data acquisition system in place means that monitoring can continue under most circumstances.

Data collected during events such as the Kaikōura earthquake can provide valuable information for both characterising performance during the event, as well as to assist in future analysis such as potential failure mode assessments. Careful consideration must be given to the scope of installed instrumentation and the frequency of monitoring in order to provide these benefits and the robustness of the system to ensure it survives large events. This robustness must extend to all aspects of the system, some of which can be geographically separated.

Damage to infrastructure

Buildings, roads and utility services suffered major damage following the Kaikōura earthquake, including closure of New Zealand's main arterial State Highway 1 and the Main Trunk Rail Line along the east coast of the South Island. Rebuild costs are estimated to be NZ$3–8 billion (Kasier et al 2017). Claims via private insurance are over NZ$1.8b as of 31 May 2017 (ICNZ 2017). Damage to buildings was widespread including as far north as Wellington where three multi-storey buildings have been demolished, because they were declared unsafe, and a number remain closed due to earthquake damage. One historic home near Kaikōura collapsed during the earthquake, which resulted in one of the two lives lost during the earthquake.

Post-earthquake dam inspections, some during the night, others the following day, were initiated across all regions that felt the earthquake. No dams failed, however, a number of irrigation and farm embankment dams in the north of the South Island were damaged and several hydropower stations tripped offline due to ground motions exceeding the thresholds of their safety devices. Reported damage to dams in the north of the South Island included longitudinal and transverse cracking, and displacement of riprap. Dam owners also reported evidence of seiches. In one case, a saddle dam with crest level 1.2 m above normal water level, was overtopped (IPENZ 2016).

Landslides and landslide dams

Tens of thousands of landslides were generated by the Kaikōura earthquake predominantly across an area of around 3,500 km^2, but some as far as 10,000 km^2 (Kaiser et al 2017). This is illustrated by the pink shaded areas on the previously shown Figure 5. The vast area in which landslides have been identified is a reflection of the topography and the complex seismic event and the numerous separate fault ruptures. Not surprisingly, the largest of the landslides occurred close to surface fault ruptures. Significant landslides along the east coast (refer Figure 9), up to 500,000 m^3, blocked New Zealand's main arterial State Highway 1 as well the Main Trunk Rail Line; both remain closed with repairs expected to be completed by the end of 2017.

At least 190 landslides dams generated by the Kaikōura earthquake have been identified (Kaiser et al 2017), predominantly in remote mountainous areas; however, many of these present significant failure consequences. The Hapuku landslide dam, refer Figure 10, formed when 10–14 million cubic metres of rock travelled 2.7 km to the valley floor (GeoNet 2017b) forming an approximately 150 m high landslide dam. Downstream populations were evacuated shortly after some of the larger landslide dams were identified due to the risk of failure. One in particular on the Clarence River, the eighth longest river in New Zealand, breached 16 hours after it was formed releasing an estimated 1,000–2,000 m^3/s in a 15 m surge of water and debris. Environment Canterbury, the regional council, set up monitoring of a small number of these dams with the highest risks of failure. Over half (approximately 56%) of naturally created dams fail within a month after formation, around a third fail over time due to sustained overtopping and erosion or slope instability caused by seepage through the dam, and the rest became semi-permanent or permanent features (Costa and Schuster 1988). Perhaps the most well-known landslide dam in New Zealand is the landslide that formed Lake Waikaremoana around 2,200 years ago (Offer 1997), which has since been developed for hydro generation; however, this was of a much larger scale compared to those formed during the Kaikōura earthquake.

Figure 9: Coastal landslides generated during Kaikōura earthquake. Photo courtesy of Sgt. Sam Shepard.

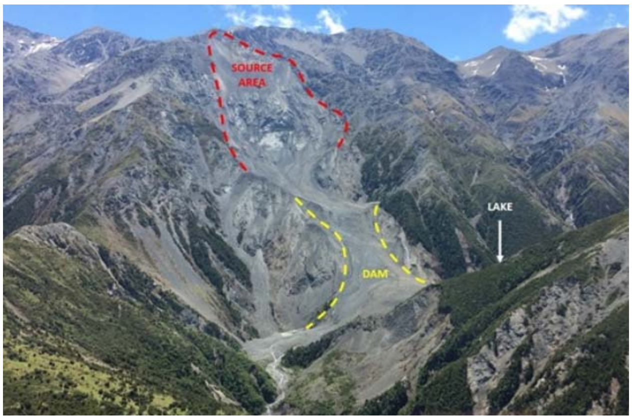

Figure 10: Hapuku landslide dam formed during the Kaikōura earthquake when 10-14 million m3 of material shifted up to 2.7 km. Image courtesy of GNS Science.

Conclusions and Summary

There are many factors that determine how energy released by an earthquake is transferred into ground motions at a given site. Fault rupture mechanisms including extent, nature of rupture, and direction of rupture typically dominate the resulting ground motions; however, there are also topographical and geological factors that can result in significantly amplified ground motions. The M_W 7.8 Kaikōura earthquake was a highly complex event, characterised by over 20 different fault ruptures with a total rupture distance of around 180 km. Fault ruptures propagated northeast from the originating epicentre and this is reflected in the recorded ground motions across the country. The highest confirmed PGAs were around 1.25g vertical and horizontal, recorded ~130 km northeast of the epicentre. Physical damage, primarily embankment cracking, occurred at some farm and irrigation dams in the top of the South Island near the earthquake epicentre. Instrumentation from dams across New Zealand shows that while most dams did not suffer physical damage, responses were measured in a number of dams and their foundations. The most common response was drop in foundation piezometric pressures, the largest a drop in pressure of up to 4m, recorded at a curved gravity dam 650 km north of the earthquake epicentre.

The response of a dam and its foundation for a set of given ground motions is influenced by a wide range of factors. This includes generic factors such as dam type and design, foundation type and construction methods. More specifically, and perhaps more significant, are factors such as the unique characteristics of the foundation, dam, or abutment material including permeability, strength, shape, stresses and any response to previous seismic events. There are also complex interactions of the dam-reservoir-foundation system including hydrodynamic effects caused by movement of the reservoir against the dam body and also the influence of the foundation flexibility. The ability to measure a response in a dam or foundation is heavily influenced by the instrumentation network and method of monitoring. Data collected during events such as the Kaikōura earthquake provides valuable information for both characterising performance during the event, and assisting future analysis such as failure mode assessments. Careful consideration must be given to the scope of installed instrumentation and the frequency of monitoring in order to provide these benefits and the robustness of the system to ensure it adequately survives the event.

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