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The performance of modular block walls reinforced with geogrid subject strong ground motions during the 2016 Kaikoura earthquake

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ABSTRACT: The existing Dashwood Bridge on State Highway 1 over the railway line was a pinch point and quite dangerous with the high number of trucks using it. The bridge was built in 1932 in a continuous 4 span concrete beam, and no longer met the NZTA seismic standards. It was decided, due to the strategic route strategy risk, that a new structure was required with improved alignment across the railway. One of the main design considerations was the seismic load case (acceleration specified was 0.6g), because the structure is located only 12km from a large earthquake of M_w = 6.5 which occurred on 21st August 2013 (17km depth, and 20km east of Seddon). The 70-week project was started in January 2014 and the Keystone TW3 walls were started at the end of June 2014 taking approximately 1 month to complete the two walls, one at each end of the culvert. The 2016 Kaikoura earthquake occurred at two minutes after midnight on 14th November 2016 in the north eastern part of the South Island of New Zealand, with magnitude M_w = 7.8. This resulted in the Keystone TW3 reinforced soil retaining walls at Dashwood being subjected to an equivalent of the design ULS seismic event, with no signs of any distress.

1 INTRODUCTION

1.1 *Background*

The existing Dashwood Bridge on State Highway 1 (SH1) over the railway line was a pinch point and had become quite dangerous due to the high number of trucks passing this point. The bridge was built in 1932 consisting of a continuous 4-span concrete beam, and no longer met the New Zealand Transport Authority (NZTA) Bridge Manual seismic standards. It was decided that, being a strategic route having a high risk of failure, a new structure was required with improved alignment across the railway. This was critical since there are limited options for alternative routes and this bridge had a record of accidents.

1.2 *Location*

The site is located on State Highway 1, 16km south of Blenheim and 7.5km north of Seddon. The Awatere fault splits into two branches 3.6km south west of the site with the southern branch passing within 1.4km of the site.

1.3 *Seismic concern*

One of the main design considerations was seismic loading, as the structure is located only 12km from the epicentre of a large earthquake of magnitude M_w = 6.5 which occurred on 21st August 2013 (at 17km focal depth, and 20km east of Seddon). Due to this combined with the general seismicity of the region, a horizontal peak ground acceleration (PGA) of 0.6g was specified for the seismic design case.

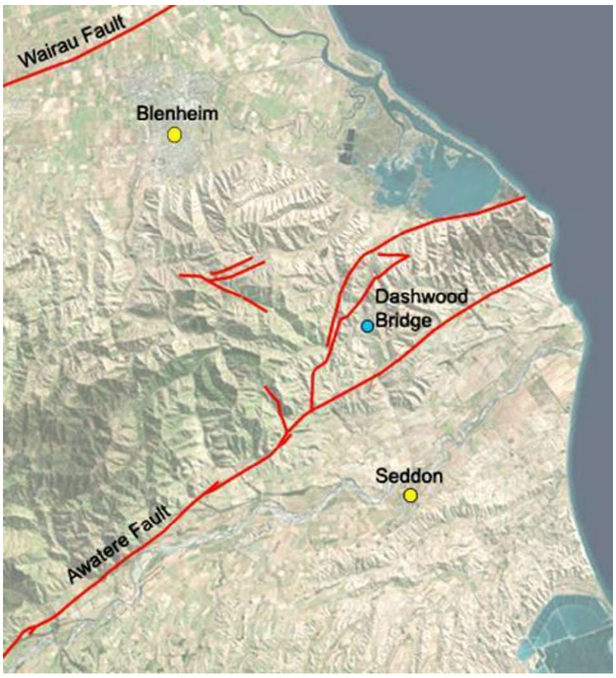

Figure 1. Location of site within Awatere fault zone. Source of map: GNS New Zealand Active Faults

2 KEYSTONE TW3WALLS

2.1 *Wall design*

The wall sections were required to provide support for the slope sides at either end of the 54m long CSP Steel Culvert. The design incorporated a Keystone TW3 modular block face and used Tensar RE500 uniaxial geogrids for soil reinforcement.

The Keystone TW3 Wall System comprises dry laid modular concrete blocks connected to Tensar uniaxial geogrids using a mechanical connector; the strength of the connection was an important consideration for design of this structure being located in a seismically active region, as mentioned above.

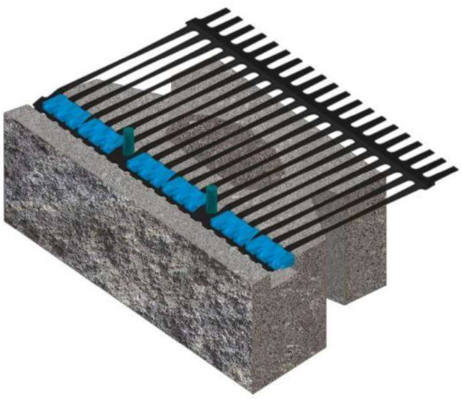

Figure 2. Keystone TW3 modular block retaining wall system

The design approach included analyses of both external and internal stability, the latter based on a 2-part wedge method, considering the various design cases in the NZTA Bridge Manual.

The basis for the 2-part wedge method of analysis is outlined in Figure 3, and has been adapted to take into account the various partial factors and recommendation given in AS 4678-2002 and is described in detail by Dobie (2012). The method uses a search technique to identify critical mechanisms. Additional global stability analyses were carried out using Bishop's routine method of slices with a circular arc to confirm the overall stability of the structure under the expected design loads. The seismic loading case was critical in both methods of analysis used.

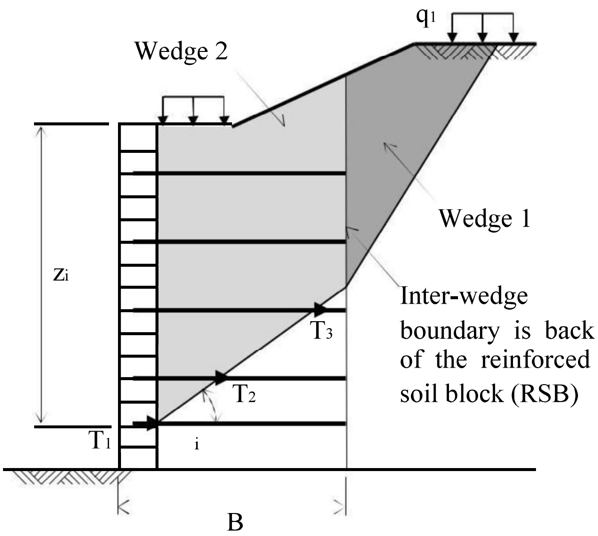

Figure 3. Basis of the two-part wedge method

The final layout had a geogrid spacing of 0.6m (every 3rd block) and a reinforcement length of up to 11m to satisfy the stability requirements, see Figure 4.

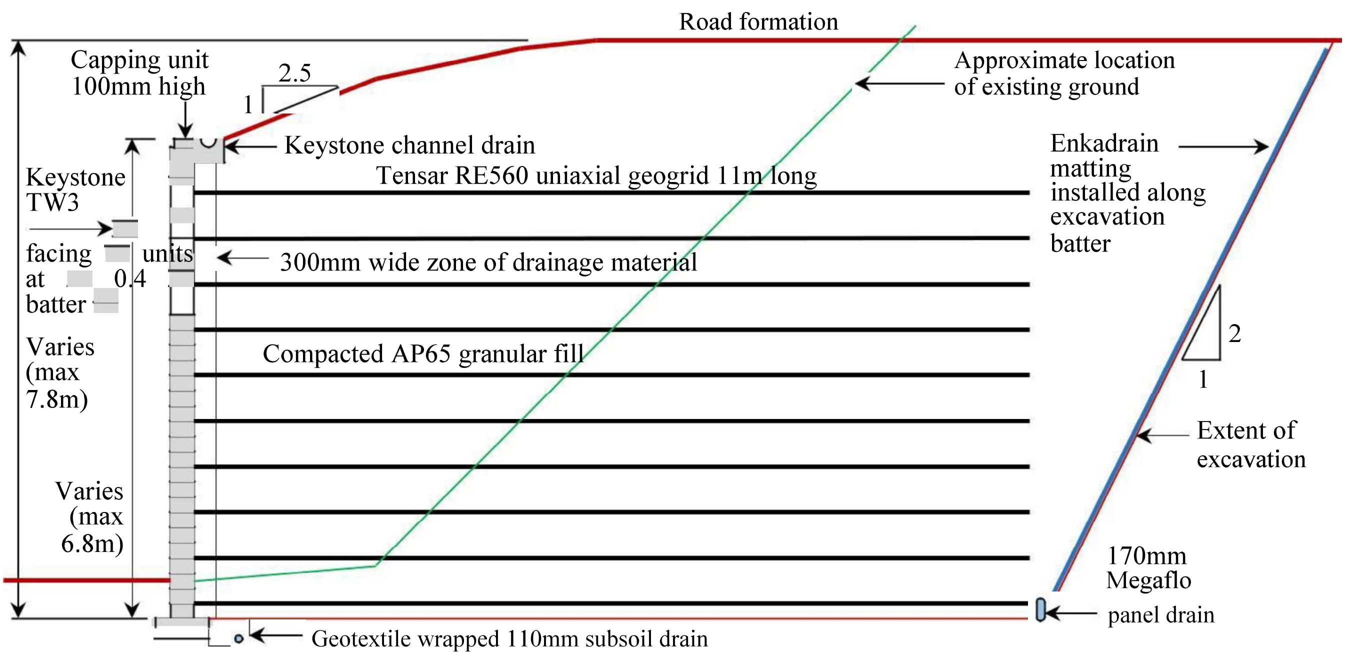

Figure 4. Keystone TW3 Eastern Wall (based on Opus Drawing 3/35/36/7544/R1)

2.2 *Construction*

The overall project duration was 70 weeks starting in January 2014 and the Keystone TW3 walls were started at the end of June 2014 and took approximately 1 month to complete, see Figures 5 and 6.

Figure 5. Keystone TW3 east wall at Dashwood at early stage

Figure 6. Keystone TW3 west wall at Dashwood completed

3 KAIKOUR EARTHQUAKE

3.1 *Outline*

The Kaikoura earthquake occurred at two minutes after midnight on 14th November 2016 (local time) due to ruptures on faults along the east coast of the Upper South Island of New Zealand and has been described as the “most complex earthquake ever studied”. The earthquake initiated in the Waiau Plains in North Canterbury and caused surface rupture on multiple faults that generally propagated northeastward over a distance of approximately 150km with maximum relative displacement of about 10m. The recorded magnitude was M_w = 7.8, with a focal depth of 15km, which was one of the strongest shallow earthquakes to occur anywhere in the world in 2016. The epicentre, being the point of initiation of the ruptures, was recorded at the southwest end of the system of faults, but the largest amount of energy released did not occur at the epicentre, but rather 100km to the northeast near Seddon, so close to the walls at Dashwood. This is important in relation to the distribution of peak ground acceleration, discussed in the next section.

3.2 *Ground motions*

New Zealand has an extensive system of stations which record the strong motion data from earthquakes. Information from these recordings is freely available from the New Zealand Geonet website (ftp.geonet.org.nz). Figure 7 shows the distribution of these recording stations in the central and upper South Island, and lower North Island. The colour of each symbol representing a recording station indicates the maximum peak ground acceleration (PGA) recorded during the Kaikoura earthquake according to the key inset in the map. The observed ground motions were strongest in the epicentral region near Culverden exceeding 1.0g in the horizonal and vertical directions with strong ground motions extending northeast towards Seddon. The closest recording stations to the Dashwood wall site are located at Seddon Fire Station (SEDS) and Blenheim Marlborough Girls College (MGCS). They are indicated with red and orange symbols close to the cross symbol which is the location of the Dashwood walls on Figure 7.

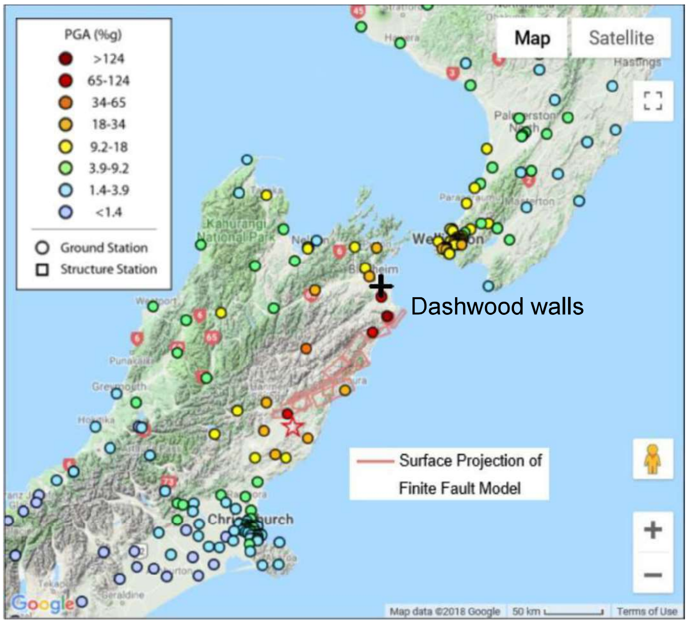

Figure 7. Locations of strong motion recording stations in relation to the Kaikoura fault break and Dashwood retaining walls (Source: CESMD and GoogleMaps)

In order to put the strong motion data into context, it is common to plot an attenuation diagram of PGA versus distance from the epicentre, which can then be related to the locations of structures of interest. How-ever, in the case of the Kaikoura earthquake, an attenuation diagram based solely on epicentral distance is misleading due to the issue mentioned in the previous section, namely that the maximum energy release occurred around 100km northeast of the epicentre.

The attenuation diagram shown in Figure 8 has been made with some adjustments to the estimated epicentral distances as outlined in Table 1:

Table 1. Assumptions used to create attenuation diagram (as shown in Figure 8)

Term	Explanation
V	Vertical component of PGA
H1 & H2	Horizontal components of PGA
Central	Stations in upper part of South Island where distance to the nearest point on the fault break has been assessed
North	Stations in North Island where distance to the epicentre has been reduced by 133km to get distance to nearest point on the fault break
South	Stations south of the epicentre where epicentral distance has been used as nearest point to the fault break

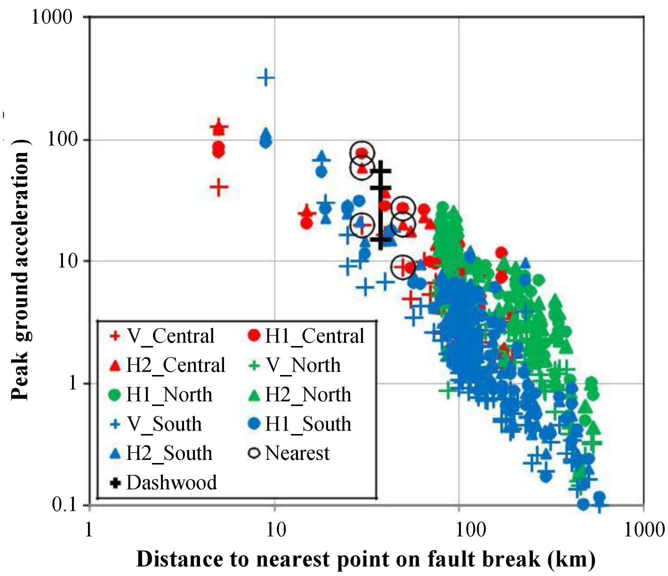

Figure 8. Attenuation of peak ground acceleration with distance from Kaikoura earthquake fault break
(Source: ftp.geonet.org.nz)

Based on these adjustments, the distance axis on Figure 8 is referred to as the “distance to nearest point on fault break” in km. Also, on Figure 8, the large black open circular symbols highlight the recordings from the two stations (SEDS and MGCS) which were mentioned previously as being closest to the Dashwood retaining walls.

Taking account of the discussion above and the data summarised in Figure 8, the estimated peak ground accelerations at the site of the Dashwood walls have been assessed by interpolating the recordings from the nearest two sites as shown in Table 2.

Table 2. Ground motion values

Site	PGA H (g)	V (g)
Blenheim Marlborough Girls College	0.27	0.09
Seddon Fire Station	0.76	0.20
Dashwood walls	0.55	0.15

The interpolation approach outlined above is supported by the contours detailed in the USGS ShakeMap for the Kaikoura earthquake, as shown in Figure 9.

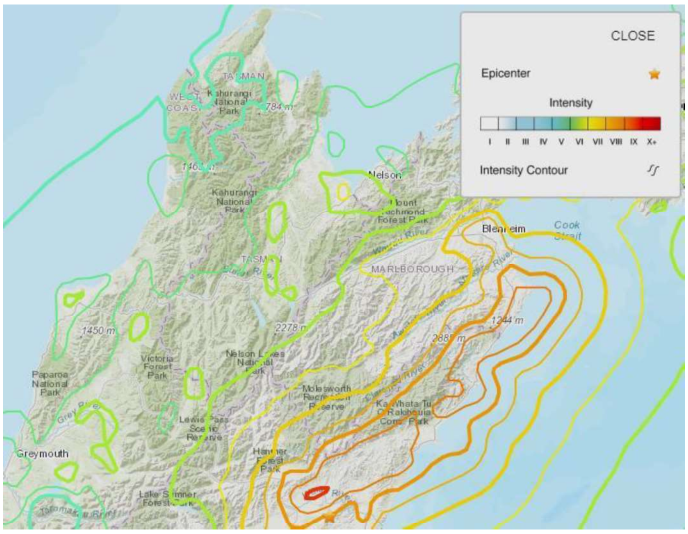

Figure 9. USGS ShakeMap for the M_w = 7.8 Kaikoura earthquake showing intensity contours
(Source: United States Geological Survey – USGS)

3.3 *Ground damage*

There was widespread damage from the Kaikoura earthquake to wineries in the Marlborough region including those in the Awatere Valley to the west of the site of the Dashwood walls and extending up to wineries located south of Blenheim.

Figure 10. Gabion wall at winery south of Blenheim

A free-standing architectural gabion wall at a winery located 7km south of Blenheim Marlborough Girls College underwent permanent deformation from the earthquake, as shown in Figure 10.

Drive through surveys along SH1 south of Blenheim included reports of cracking along the roadside as well as settlements of up to 30cm in the bridge abutment approaches. Detailed inspections were not carried out in this area except near locations of strong ground motion stations.

4 PERFORMANCE REVIEW

4.1 *Condition of retaining walls post-earthquake*

The image below in Figure 11 shows a similar view after the earthquake as the “before” photo in Figure 6.

Figure 11. Keystone TW3 western wall in early 2018

Figure 12. Views of swale drains

The inspection of the walls showed no sign of movement both vertically outwards and in horizontal alignment. The clearest evidence is shown by the images in Figure 12 of the swale drains. There is no separation of the swale drain from the top of the wall and no observed cracks in the fill above the wall.

A slip joint was designed into the wall to accommodate differential settlement at the transition where the wall extends up the sides of the culvert at an angle. There has been some minor relative movement of the upslope section (<10mm) however it is unknown if this had occurred as a result of the earthquake shaking or under normal loading conditions. Figures 13 and 14 show the slip joint both pre- and post-earthquake.

Figure 13. Slip joint pre-earthquake

Figure 14. Slip joint post-earthquake

It is clear from these photos that the walls have performed extremely well during the strong shaking which took place during the Kaikoura earthquake with no signs of distress.

4.2 *Back-analysis of the wall cross-section*

As mentioned in Section 1.3, the design of the Dashwood walls was carried out assuming a peak ground acceleration of 0.6g in the horizontal direction only. The internal stability analysis using the 2-part wedge method described in Section 2.1 resulted in a cross-section which was satisfactory for this loading.

The attenuation diagram shown in Figure 8 indicates that vertical acceleration was also significant, especially in the area close to the fault break, and Table 2 gives estimated peak ground accelerations of 0.55g horizontal (K_h) and 0.15g vertical (K_v) at the site of the Dashwood retaining walls. The 2-part wedge method can take account of vertical acceleration as well as horizontal acceleration in internal stability analysis. Therefore, in order to investigate the critical mechanisms, K_h was set to 0.55g, and K_v was gradually increased until unstable wedges appeared.

The results of this investigation are shown in Figure 15, which shows all wedges (lower boundaries of each Wedge 2 as defined in Figure 3) crossing the reinforced soil mass as coloured lines. Green lines have adequate margin against failure, and red or pink lines indicate cases where factored resisting force is less than factored driving force. There are five very low angle wedges with a pink colour near the base of the structure indicating the critical mechanisms which first appear at K_v = 0.1g. The appearance of these wedges at very low angles at the base of the rein-forced soil mass is the normal critical behaviour expected in a case of very strong seismic shaking. In this analysis, K_v is applied both upwards and down-wards, and these critical mechanisms are for the case of K_v upwards, which is also the normal case.

Although unsatisfactory, the pink wedges below would not necessarily indicate a failure condition, but rather a condition where factored resisting forces are less than factored driving forces. This confirms the satisfactory initial design for the Dashwood walls, as well as the importance of considering the effects of vertical acceleration in the design of reinforced soil structures. In this case, the vector acceleration of K_h = 0.55g and K_v = 0.1g is 0.56g with an upward inclination of 10 degrees. This is a seismic loading situation which should be considered and investigated as part of the seismic design of a reinforced structure.

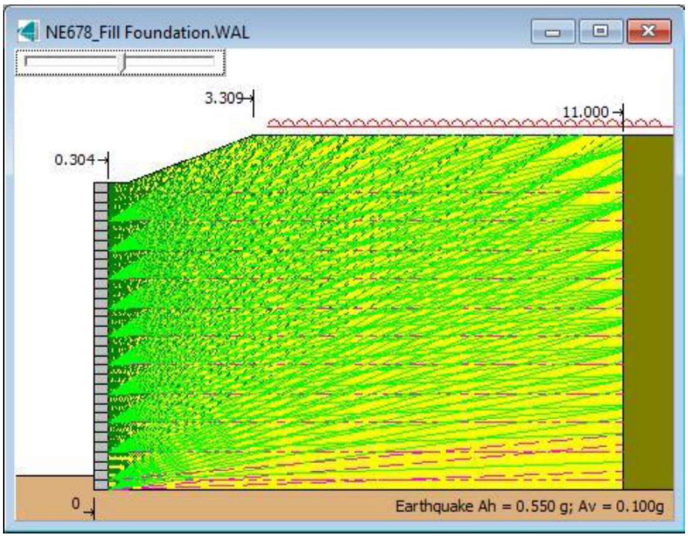

Figure 15. Back-analysis of internal stability

5 CONCLUSIONS

The excellent seismic performance of Tensar reinforced soil retaining walls is well known based on experience during previous strong earthquakes such as Kobe in 1995 and Chi Chi in 1999. During the more recent series of earthquakes which affected Christchurch, the specific case of a reinforced soil retaining wall on the edge of the Avon River in Hagley Park was investigated and reported by Dobie et al (2012). This wall was located close to the epicentre of the 21st February 2011 event (M_w = 6.3) with K_h and K_v both estimated at about 0.4g and there were no signs of damage or deformation. The performance of the Dashwood walls confirms the excellent behaviour of geogrid reinforced structures in strong earthquakes.

One important contribution to this excellent performance is the ductility of these structures which are able to deform during the strong motions created by the earthquake and absorb energy while retaining their function. Research at the University of California – San Diego investigated the seismic behaviour of a 6m high wall subjected to peak ground acceleration of K_h = 0.55g on a shaking table, see Sander et al (2014). These previous data are consistent with the very good performance of the two walls at Dashwood. In all cases the retaining wall systems included a positive connection between the geogrid and the facing. This is an important feature of any reinforced soil retaining wall system to be used in seismic areas.

The performance of the Keystone TW3 modular block walls at Dashwood bridge supports the design approach adopted for reinforced soil walls located in seismically active regions. The back-analysis summarised in Section 4.2 indicates the importance of considering combinations of horizontal and vertical accelerations to find the worst design case.

REFERENCES

Dobie, M. J. D. 2012. Design of reinforced soil structures using a two-part wedge mechanism based on AS 24678-2002. *Proceedings ANZ2012, Melbourne, Australia.*

Dobie, M. J. D., Stevens, G.R. & Collin, S.J. 2012. Performance of a reinforced soil retaining wall during the Christchurch earthquakes. *Proceedings ANZ2012, Melbourne, Australia.*

GeoNet. 2016. ftp://ftp.geonet.org.nz/strong/processed/Proc/Summary/2016/ See 2016p858000_pga.csv

GNS Science New Zealand Active Faults Database URL: https://data.gns.cri.nz/af/

Sander, A.C., Fox, P.J. & Elgamal, A. 2014. Full-scale seismic tests of MSE retaining wall at UCSD. *Geo-Congress 2014 Technical papers, GSP 234, ASCE, USA.*

USGS Interactive Map (2016) URL: https://earthquake.usgs.gov/earthquakes/eventpage/us1000778i/map