11 SEISMIC DAMAGE

11.1 INTRODUCTION

This section is intended to provide a strategy for undertaking bridge inspections following a significant earthquake, and to give guidance on where to look for, and how to evaluate, damage to typical highway bridges in New Zealand.

It does not cover very large or special structures. Obvious problems such as fallen spans or other extreme damage, where the severity of the damage is self evident, are not discussed. It does not cover damage repair, and it strongly recommends that design advice be obtained before repairs are carried out.

Emergency work to open the bridge, or to clear roads or waterways below may sometimes commence very shortly after the earthquake. Even if total demolition is going to be the final fate of the bridge it is desirable to investigate, record and photograph the damage before the evidence is destroyed. It is preferable that this work be done by an experienced bridge designer, who has experience in forensic investigation of seismic damage and who is not involved in the emergency work. If there is an authorised New Zealand National Society for Earthquake Engineering reconnaissance team in the area they will be able to assist and should be given access to the site.

11.2 OBJECTIVES

The overall objectives of seismic damage assessment are to:

- Minimise loss of life;
- Minimise the economic loss to the region.

For the roading network, the hierarchy of objectives will be to ensure the safety of:

- Bridges known to be vulnerable, with potential for loss of life;
- Primary routes for the passage of emergency vehicles concerned with the saving of life and property;
- Primary routes for the passage of vehicles concerned with the distribution of essential supplies and restoration of essential services;
- Secondary routes for the passage of emergency vehicles;
- All routes for general use.

11.3 STRATEGY AND INSPECTION LEVELS

To ensure that a route or network is safe for the public, bridges should be inspected following an earthquake of sufficient intensity to cause concern about the possibility of damage. All bridges within an area subjected to MM VIII intensity shaking or greater should be inspected. Two levels of inspection are appropriate:

- A Preliminary Safety Check, conducted immediately following the earthquake to check for safety for immediate use and for obvious damage;
- A Detailed Structural Check, which may or may not be required, and which would be conducted at some later time.

In most areas of the country, seismic screening of the State Highway bridges will have already identified those bridges likely to be most vulnerable to damage with potential to cause loss of life.

11.4 PRELIMINARY SAFETY CHECK

The following order of priority should be considered for the Preliminary Safety Check of the bridges:

- Inspect first those bridges known to be most vulnerable with potential for loss of life (e.g. as identified by the seismic screening), giving priority to those carrying the highest traffic volumes;
- Inspect all other bridges along the primary routes required for the passage of emergency vehicles concerned with the saving of life and property;
- Inspect all other bridges along other primary routes required for the distribution of essential supplies and restoration of essential services;
- Inspect all remaining bridges.

Each bridge should be examined quickly but with sufficient care to identify problems that could lead to collapse and compromise public safety.

Fortunately, serious damage can often be detected at road level. Nevertheless the underside of the deck and the substructure should also be briefly examined.

The bridge and approach embankments should be observed for signs of settlement, which is a very common form of earthquake damage (see Sections 6 and 9). Vertical settlement may not be a cause for immediate concern other than from the road safety aspect. However, it is likely to have increased the loading on abutment piles through down-drag. If it is also associated with horizontal movement of the ground, especially towards the bridge, the abutment may have been moved as well. This has a consequence for foundations, bearings and expansion joints. Such ground movement may extend to the adjacent pier as well, with similar consequences.

Settlement of approaches may have damaged services in the ground. If it causes water to leak, further damage from washouts may later eventuate.

At the bridge, the lines of the handrails, kerbs and centreline markings should be checked for horizontal and vertical discontinuities as these will be quick indicators of problems below. Differential settlement between piers and abutments, of any one support relative to the others, may indicate serious damage to substructure members. Also, it will alter the stress distribution in continuous superstructures which could lead to overstressing and damage at some sections.

Other indicators of problems that can be seen at deck level are:

- Evidence of excessive movement of expansion joints during the earthquake;
- Expansion joints closed up;
- Knock-off devices at abutment backwalls displaced backwards and / or upwards by impact;
- Spalling of kerbs and decks either side of expansion joints;
- Buckling of handrails or traffic barriers.

A visual inspection below the bridge should reveal obvious damage such as:

- Bearing failures or bearings having "walked";
- Linkage and shear key failures;
- Cracking or spalling and yielding of abutments and piers;
- Movement of abutments and piers;
- Damage to exposed piles.

If damage is found, several courses of action can be taken. The bridge may be:

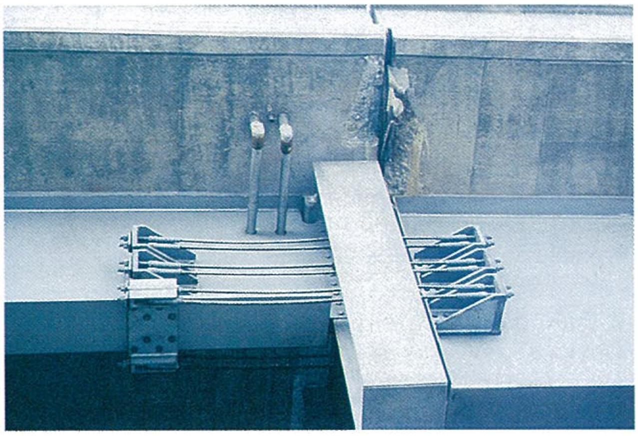

Figure 11.1: Spalling damage at expansion joint.

- Left open to the public unrestricted, but noted for a Detailed Structural Check at a later date;
- Left open to the public but with restricted speeds and/or axle loads;
- Left open only for emergency vehicles;
- Closed until temporary repairs are completed or until shoring has been installed;
- Closed indefinitely.

In deciding on what course of action to take, the engineer should take account of the risk of the bridge collapsing against the consequences of placing restrictions on it. That in turn will depend on the importance of the route and the alternatives available. The likely effect of aftershocks should also be considered.

It should be remembered that a bridge can sustain a great deal of superficial damage including loss of cover concrete without the vertical load-carrying capacity being affected too greatly.

Lastly, any damage discovered should be recorded, photographed, and confirmed as recent and likely to have been caused by the earthquake.

11.5 DETAILED STRUCTURAL CHECK

11.5.1 Approach Embankments

High approach embankments on soft ground are notorious for settling or slumping in earthquakes. If settlement is associated with failure of underlying soils, especially liquefaction, then soil flow through the abutment is likely to have occurred.

If lateral displacement has occurred it can be detected by such evidence as:

- Heave at the toe of the embankment;
- Longitudinal cracking of the approach road surface;
- Movement of the abutment;
- Sand volcanoes and / or ground cracking on the flat ground.

Soil flow through the abutments will increase the lateral load on piles and it may have caused damage to them that can only be seen by excavation. If the rotational and lateral movements of the abutment can be quantified it may be possible to carry out a back analysis which gives an indication of the risk of pile damage. Abutments on raked pile groups cannot sustain much movement without damage.

Flow through the abutments can occur even where there are no approach embankments but where the natural ground is weak. There are many recorded cases of river banks moving closer together in earthquakes (usually but not necessarily associated with liquefaction).

See also Sections 6 and 9.

11.5.2 Abutments

Apart from the problems with moving ground discussed above, abutments are vulnerable in other ways. Particularly with more recently designed bridges, the superstructures are often designed to act independently of abutments in an earthquake and large relative movements between the abutment and the superstructure can take place. If the intensity was sufficient to cause yielding in the substructure this relative movement could be greater than that provided for normal service. In such cases damage is likely to include:

- Hammering and concrete spalling;
- Failure of expansion joints or at least of their seals;
- Knock-off devices displaced backward and/or upwards;
- Linkage hardware distressed;
- Shear keys damaged.

Such damage is considered to be acceptable, repairable and not necessarily cause for closing the bridge completely.

In the ideal situation, bearings should still cope with post-elastic movements but they should be checked carefully for damage.

Where the abutment is independent of longitudinal superstructure movements but provides lateral restraint, the mechanism for providing that restraint should be checked, i.e. check for damage to shear keys, linkage devices, mechanical dampers, etc.

11.5.3 Piers

Cracking of piers to a greater or lesser extent should be noted, and considered on a case-by-case basis for sealing, repair, encasing or replacing.

The piers are the visible part of the substructure and ideally are the locations chosen by designers for the development of plastic hinges in the design intensity earthquakes.

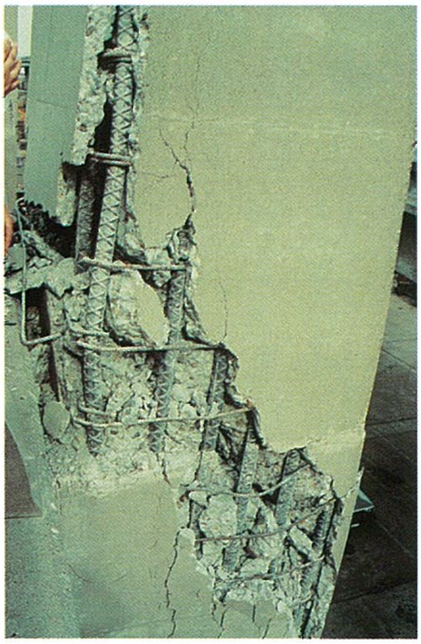

Figure 11.2: Ineffective confinement in a column.

For modern bridges at least, spalling of cover concrete at the top or bottom of piers may indicate that the bridge has been subject to a design intensity earthquake and has yielded according to prediction.

If the reinforcing cage is largely intact and the core concrete properly confined, the vertical load capacity is likely to be adequate. Repairs will be required but it may be possible to carry them out with the bridge in service.

Piers should be checked for verticality. If they have moved out of plumb significantly during the earthquake the reason should be determined. If it is caused by yielding of the pier and displacement of the superstructure then it may be desirable to straighten them before repairs to the yield zones are attempted. However, if piers are out of plumb and the superstructure is not displaced, there is a strong inference of foundation displacement.

11.5.4 Foundations

The foundations are the hidden part of the substructure and ideally, in modern (post–1972) bridges, have been designed with sufficient overstrength to ensure they remain elastic up to and after the bridge structure has started to form a collapse mechanism.

However, that design approach will not have been applied in older bridges, and even in modern bridges that ideal is not always achieved and piles can yield.

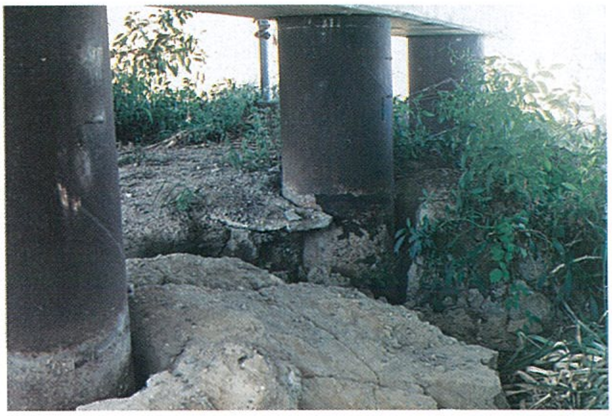

Figure 11.3: Movement of piles in the ground.

Tell tale signs are:

- Large relative movements between piles and the soils;
- Relative displacement between pile caps;
- Piers out of plumb.

From each of these signs a deflection of the top of the pile can be measured and a back analysis using a range of soil parameters can be used to indicate the likelihood of pile yielding. The final check is to dig them out and examine them but usually that is not easy to do.

Vertical displacement of piles does not always mean that pile yielding has taken place, particularly if there are no raked piles in the group. Furthermore, temporary loss of bearing capacity (e.g. from liquefaction) does not necessarily mean that capacity is lost permanently.

Vertical displacement can have serious consequences for the superstructure and particularly so for indeterminate (continuous) spans. The effect should be assessed.

For simply supported spans, the rotational capacity of bearings may have been exceeded because of the settlement.

For short deep continuous spans, distress could have been caused by small settlements that are only detected by taking levels. This should be considered as part of a thorough investigation.

See also Section 9.

11.5.5 Linkage Devices and Shear Keys

Linkage devices and shear keys are installed in bridges to limit relative movements between adjacent spans, and between spans and their supports. If they have been worked very hard by the earthquake they may have been damaged and require replacement.

To check the linkages properly it may be necessary to remove some for close inspection.

See also Sections 8.6 and 8.8.

11.5.6 Expansion Joints

Expansion joints that have operated beyond their design range may be damaged and require repair or replacement. Many joints have very little capacity for lateral displacement and damage can be caused by very small movement.

See also Section 8.3.

11.5.7 Holding Down Bolts

Holding down bolts that have been subject to large transverse shears are likely to have yielded. That does not necessarily mean that replacement is required. Recent design practice is to provide no holding down bolts at all in most cases. Each case should be assessed on its merit.

See also Section 8.5.

11.5.8 Bearings

Bearings are vulnerable in earthquakes, particularly if they are also required to carry transverse shear.
(a) Elastomeric Bearings

Bearings that have been deflected beyond their design shear may be ruptured internally, but usually damage manifests itself at the surface and can be seen.

Deep lead-rubber bearings are used for base isolation and can be subject to large lateral deflections. They should be carefully checked after an earthquake. If there is any suspicion of damage it may be necessary to remove one and check its capacity for continued performance.

Bearings not positively restrained in position may "walk". There is a recorded case of a lead-rubber bearing escaping from its keeper ring during an earthquake.

(b) Sliding Bearings

If the design capacity for sliding has been exceeded, damage is likely.

(c) Pot Stay Bearings

If a pot stay bearing has failed in shear it will be obvious.

See also Section 8.4.

11.6 INVESTIGATION REPORT

The results of the investigation should be recorded in a report that includes:

- An assessment of the ground acceleration at the site.
- An assessment of how the loads were transmitted to and from the ground and their magnitude (i.e. trace the load paths).
- A record, including photographs, of damage and permanent deformations.

One of the potential difficulties of investigating earthquake damage is confirming that all the damage observed occurred during the earthquake . If investigation is sufficiently soon after the event it is easier to differentiate between new and old damage.