Dams Safety Committee

NEW SOUTH WALES

DSC3C

June 2010

ACCEPTABLE EARTHQUAKE CAPACITY FOR DAMS

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1. INTRODUCTION

The *normal requirements* of the NSW Dams Safety Committee (DSC) are set out in its guidance sheets with its principal guidance sheet, *DSC Background, Functions and Operations - DSC1A,* outlining the DSC's general operations and authority.

The DSC has statutory functions under the *Dams Safety Act, 1978* to ensure that all prescribed dams in NSW are designed, constructed, maintained and operated to a standard where risks to the community are tolerably low. The level of risk is determined by the likelihood and consequences of failure. Earthquake (seismic) activity affecting dams is one of the risk elements that must be considered by dam owners.

Owners, and their professional advisers, have full responsibility for ensuring the seismic safety of their dams, each with their own individual and specific issues. However, the DSC also has a responsibility to draw owners' attention to any DSC requirements (see section 2.2), as well as general issues or findings that may provide guidance to assist owners to achieve *good practice* for the seismic safety management of dams.

The DSC Seismic Safety Goal and Key Requirements (Section 2) at the start of the sheet are a summary - the whole sheet is to be read for a proper understanding of DSC considerations on acceptable earthquake capacity for dams.

2. DSC SEISMIC SAFETY GOAL & KEY REQUIREMENTS

2.1 DSC Seismic Safety Goal

The DSC's goal regarding the seismic safety of prescribed dams is to ensure they are appropriately designed (e.g. have adequate stability) and managed to result in tolerable risks to community interests.

It is for the dam owner to determine how this goal (including DSC requirements) will be achieved and to demonstrate to the DSC that the goal is achieved or will be achieved following safety improvements. The following sheet sections aim to provide guidance to assist dam owners in achieving this DSC goal.

2.2 DSC Key Requirements

This section summarises the DSC requirements outlined in this sheet.

5.1 General

Check all new or proposed significant, high and extreme Consequence Category dams for safety under seismic loadings. All existing extreme, high and significant Consequence Category dams are to be subject to an appropriate safety under earthquake study and its status reviewed at each 5 yearly surveillance report.

5.2 Design Criteria

All extreme, high and significant Consequence Category dams are to withstand earthquake shaking for the appropriate Maximum Design Earthquake (MDE) from Table 5.3 of this sheet. For extreme and high Consequence Category dams, obtain seismic loadings from an experienced seismologist who is familiar with the characteristics of earthquakes in Australia. In taking guidance from ANCOLD(1998), read the guidelines in conjunction with the paper Fell(2005).

5.4 Design Analysis for Concrete Dams

For extreme and high Consequence Category concrete dams, base the design on an accepted dynamic analysis.

5.5 Design Analysis for Earthfill Dams

For all extreme, high and significant Consequence Category embankment dams determine whether the dam or foundation is potentially subject to liquefaction and report the determination to the DSC. For extreme, high and significant Consequence Category earthfill dams carry out a staged stability analysis based on the procedure outlined in Section 6 of the ANCOLD earthquake guidelines.

5.7 Design Analysis for Rockfill Dams

Concrete faced rockfill dams of free-draining rockfill are often designed empirically on the basis of precedent performance. The DSC will accept such a design basis. Analyse dams of rockfill that are not free-draining, in a similar manner to earthfill dams and current best practice.

5.8 Appurtenant Structures

The design of appurtenant structures where they are relevant to dam safety shall be in accordance with Section 8 of the ANCOLD Guidelines.

5.9 Defensive Measures

For extreme, high and significant Consequence Category dams, particularly embankment dams employ appropriate defensive measures.

5.10 Upstream Occurrences

Consider the potential for reservoir rim landslides to be triggered by earthquake and for reservoir seiche and report on a qualitative assessment of the implications for the safety of all extreme, high and significant Consequence Category dams.

5.11 Post Earthquake Procedures

The DSC considers that there is a considerable risk to dam safety for some time after an earthquake an analysis of safety under the subsequent event should undertaken.

Dam owner's are required to have in place an effective Dam Safety Emergency Plan (DSEP) prepared in accordance with the DSC's guidance sheet on *Emergency Management for Dams (DSC2G)*.

5.12 Summary

The DSC will consider deviations from these requirements upon submission of a cogent and fully documented case. In particular, if Risk Assessment methodologies are used they should be in accordance with the ANCOLD Guidelines and follow the requirements of *Demonstration of Safety for Dams - DSC2D*.

3. BACKGROUND

Australia is a landmass of comparatively low seismic activity. It is well removed from the tectonic plate margins which are the most seismically active parts of the earth's crust.

Nevertheless earthquakes of a magnitude with the potential to cause damage to structures do occur in Australia from time to time due to a gradual build up of intra plate stresses. Over recent decades the 1968 Meckering event (M6.9), the 1988 Tennant Creek events (largest M6.8) and the 1989 Newcastle event (M5.6) have confirmed the potential for damaging earthquakes. The symbol M refers to Richter magnitude, either M_L (based on records of local waves) or Ms (based on records of surface waves). The values are approximate since they vary in published sources. Overseas experience shows that very large earthquakes are possible in intraplate environments. A notable example is the New Madrid, Missouri event of 1812 (M8.3). Although exceptional intraplate events are rare they must be considered in dam safety given the potentially long life of dams and the very low risks of dam failure that are acceptable. If necessary, retrofitting of existing dams must be implemented to cater for such events. In Eastern Australia the present advice by seismologists is that the upper limit magnitude that could be expected is M7.5.

In Australia, the Newcastle event was significant in that, being located close to a major urban centre, it was the first earthquake to cause loss of life in this country. All three events in Australia mentioned in the preceding paragraph caused structural damage but again the Newcastle event was by far the most damaging, due to its location close to a large city, with a damage estimate totalling some $l,000M in the prices of the day. In contrast, the Meckering and Tennant Creek events occurred in remote areas. It is important to note that the Newcastle Earthquake of 1989 was not an exceptional event. There are two other earthquakes exceeding M5 that have occurred in the Newcastle area in the past 130 years and there are two further events in the early 1840's which caused strong shaking in the Hunter Valley.

Understanding of Australian earthquakes has grown rapidly over the past two decades. Much is still being learned through improved monitoring of seismic events. Dam owners are thus encouraged to participate in the development and operation of seismic monitoring networks. The availability of additional data will assist in providing a more balanced decision making process in the design of new dams and assessment of existing dams.

Generally dams withstand earthquake shaking remarkably well. There are very few recorded instances of dam failure resulting from earthquakes, although many dams have suffered deformation and damages. For instance, the M8.0 Wenchuan earthquake of 12 May 2008 in China damaged over 1500 dams, some seriously, but no dam failed.

ICOLD (1995) has reported the results of a survey of dam failures among its national committees. Of 183 failures, at most 5 were related to earthquake. In comparison, 45 failed due to overtopping by flood. ICOLD give earthquake as the cause of failure or distress of:

- Embalse Aromos Dam, Chile, in 1985
- Lliu-Lliu Dam, Chile, in 1985

- Van Norman Dam, USA, in 1971

Liquefaction, presumably resulting from earthquake, was the cause of failure for:

- Sheffield Dam, USA IN 1925
- Niznhe Svirskaya Dam, USSR, in 1935

Note that ‘failure” by the ICOLD definition was an inability to retain water, and not necessarily release of the reservoir. The reservoir was not released in the case of Van Norman Dam, at least, because of a fortuitously low storage level when the earthquake occurred.

Reports of the performance of dams under earthquake shaking have also been provided by Seed (1981), Hinks and Gosschalk (1993) and USCOLD (1992). These sources show that there have been cases of damage, and some of failure. In summary, there have been:

- Some 20 to 30 failures of earth dams, most, perhaps all, involving liquefaction of cohesion less soils. Most also were low dams less than 20m high and did not result in loss of life. However, the failure of three tailings dams in Chile caused the loss of 254 lives.
- There have been no failures of rockfill dams
- There have been no failures of concrete dams

Concrete dams may be subject to severe cracking, movement and opening of joints which, if they do not cause failure, may render the dam unserviceable or may require major repairs.

To date there is no recorded failure of a large concrete dam as a result of earthquake shaking. However in September 1999, the Shih-Kung dam in Taiwan was severely affected by a nearby Richter 7.4 earthquake, which initiated movement in a fault line running under its gated spillway concrete section. One end of the spillway (6 gates) was sheared from the rest of the spillway (2 gates) and lifted over 9m. As such the construction of inelastic dams over known faults should be treated with extreme caution.

In 1971, the 113m Pacoima arch dam (near Los Angeles, California) experienced a M6.6 shock at 6.4km distance which resulted in a peak acceleration at the site of l.2g. The dam suffered damage but did not fail and, after repairs, was returned to service. (Swanson and Sharma, 1979).

In 1967 the 103m high Koyna gravity dam in India suffered a near field M6.5 earthquake. Major cracking occurred but the dam did not fail. (Saini et al., 1972).

Embankment dams can suffer two main types of damage, depending on the nature of foundation or fill materials and the design and construction standards:

- major deformations, slumping and cracking; which could lead to failure from loss of freeboard or piping along cracks.
- liquefaction of either the foundation material or the dam fill.

In 1989 the M7.1 Loma Prieta earthquake damaged Austrian Dam in California. The 56m high earthfill dam suffered crest settlement up to 760mm with associated major cracking, including deep transverse cracks near the abutments and significant spillway damage. The separation of the embankment from the spillway wall was up to 300mm wide and 7.2m deep (Forster and MacDonald, 1998). The storage level was low at the time. No liquefaction was involved at this dam. The dam was repaired and returned to service. (Rodda et al., 1990).

In 1987 the 86m high Matahina Dam in New Zealand, an earth core rockfill structure, was strongly shaken by an earthquake of M6.3 centred some 23km away. The occurrence of delayed piping (over nine months after the earthquake), presumably triggered by this earthquake, may well have been fatal to the dam, had there not been intervention to arrest the process and make repairs. There was no liquefaction involved in this incident (Gillon and Newton, 1994). This experience indicates that enhanced surveillance after an earthquake needs to be maintained for a substantial period.

Coleman and Rogers Dams, Nevada, USA failed as a result of the Fallon earthquake, apparently at the interface between the concrete and the embankment structures (Ambrasseys, 1960). There was apparently no liquefaction involved.

Liquefaction can occur in saturated, loose, fine-grained cohesion less materials. The embankments of hydraulic fill or tailings dams may be subject to liquefaction. In Australia though, the main risk of liquefaction for dams, other than tailings dams, would relate to alluvial foundation materials that support dam embankments. This is because embankments in this country are traditionally constructed of either cohesive materials or rockfill; the hydraulic fill technique was never employed to any significant extent.

In 1971, the hydraulic fill embankment of the Lower van Norman Dam in California suffered a near disastrous failure due to liquefaction. A massive upstream slide occurred and the dam lost 9m height from its crest. It was only good fortune that the storage was 7.5m below full supply level at the time. If the storage had been at full supply level it seems certain that the dam would have failed. (Seed, 1982).

In 1925 the 11m high Sheffield Dam near Santa Barbara, California failed completely due to earthquake. It is believed the failure involved liquefaction. (Seed, 1982).

Free draining rockfill dams with a thin impervious element are regarded as inherently stable under earthquake shaking. This is particularly so for concrete faced rockfill dams and upstream sloping core rockfill dams which have a large mass of drained rockfill so that earthquake effects cannot cause reduced stability due to high pore pressures (Cooke, 1984). This is evidenced by the Cogoti Dam

(Chile), which in 1943 experienced ground accelerations estimated to be in the range 0.15g to 0.30g. This 159m high dam is a dumped rockfill structure with an impervious upstream facing of laminated concrete. The crest settled 280mm and there were minor rock slides on the l.8H: lV downstream face (Cooke, 1984).

However, Seed et al. (1985) pointed out that modern concrete faced compacted rockfill dams had not yet been subjected to strong earthquake shaking (over 0.20g) and their performance remained untested. Since then in 1994, Cogswell Dam, a large concrete faced compacted rockfill dam in Southern California, and Cogoti Dam (Chile), again in 1997, have been subjected to strong earthquake shaking (over 0.25g) with minimal distress (i.e. minor settlement).

In the Wenchuan M8.0 earthquake of May 2008, the 156m high Zipingpu concrete faced rockfill dam was subjected to severe shaking, being only 17km from the epicentre. The peak ground acceleration was 0.5g and the peak acceleration at the dam crest was 2.0g. The crest immediately settled 684mm and within a few days the settlement had reached 744mm. The crest was displaced 200mm downstream and the face slabs were severely damaged. However, the dam did not fail and was judged safe by the post-earthquake review team (Xu Zeping, 2008).

In 1984 the Leroy Anderson Dam (California) experienced a peak ground acceleration of 0.40g. The 72m high earth core rockfill dam (dumped and sluiced rockfill) sustained two systems of longitudinal cracks which apparently resulted from differential settlement between the core and the shells. The crest settled l5mm and moved 9mm downstream. (Bureau et al., 1985).

Earthquakes can trigger reservoir rim slides that in turn could lead to dam failure by creating a wave that overtops the dam. Earthquakes can cause a seiche in the reservoir that can overtop the dam as occurred at Hebgen Dam (USCOLD, 1992). Outlet towers, bridges and other appurtenant structures have failed due to seismic loading; such failures do not usually endanger the dam, but could result in an uncontrolled loss of storage.

4. DSC APPROACH TO SEISMIC RISK IN DAMS

In compiling this guidance sheet the DSC has been conscious of the following factors:

- Available data suggests that there is a low probability of failure under seismic loading for well designed and constructed dams on sound foundations. Nearly all cases of dam failure due to earthquake seem to be related to the liquefaction of saturated, cohesionless material, although incidents have occurred that point to the potential for failure where there is no possibility of liquefaction.
- Relative to the situation in other, more earthquake prone countries, seismic design methodology for dams is reasonably well developed in Australia but there are few highly experienced practitioners.

- Much of the design methodologies in use in Australia has been developed for the United States but have some application to Australian conditions despite the differing characteristics of seismic events in the two countries.

With the potential low probability of failure due to earthquake in mind, the DSC has set its minimum requirements given in this sheet. They allow a phased approach to ensure that designers give proper consideration to adequate earthquake loading, both in design of new dams and when reviewing the safety of existing dams.

The DSC endorses the 1998 ANCOLD *Guidelines for the Design of Dams for Earthquakes* as the basis for the DSC's requirements, except that aspects dealing with risk assessment should be modified in accordance with the ANCOLD *Guidelines on Risk Assessment - 2003*. The ANCOLD guidelines should be read in conjunction with Fell (2005) which outlines some later developments.

The ANCOLD earthquake guidelines contain a comprehensive list of methodologies and reference documents to assist dam owners. The DSC's overall requirement is that the degree of analysis adopted should reflect the consequences of failure, the type of dam, the local seismicity and the nature of the foundations.

Designers are invited to submit alternative approaches to these requirements if they consider the latter to be inappropriate in particular circumstances. The DSC will carefully consider any cogent and well documented case supporting the use of alternative approaches.

5. DSC SEISMIC REQUIREMENTS FOR DAMS

5.1 General

5.1.1 Check all new or proposed significant, high and extreme Consequence Category dams for safety under seismic loadings. The DSC notes that in most cases the concurrent occurrence of significant flood and earthquake events is of too low a probability to be considered.

5.1.2 The DSC has no requirements regarding the design of low Consequence Category dams for earthquake loading.

5.1.3 All existing extreme, high and significant Consequence Category dams are to be subject to an appropriate safety under earthquake study and its current status reviewed at each 5 yearly surveillance report (unless the DSC requests otherwise.)

5.2 Design Criteria

5.2.1 All extreme, high and significant Consequence Category dams are to withstand earthquake shaking, without an uncontrolled loss of storage due to partial or complete failure of the dam, for the appropriate Maximum Design Earthquake (MDE) from Table 5.3 of this sheet. Considerable damage in such an event would be acceptable.

5.2.2 The DSC requires all dams to meet these standards but will consider studying alternative standards based on appropriate risk assessment. However, in such cases, the dams are also required to meet the provisions of Section 5.11 'Post Earthquake procedures' of this sheet.

5.2.3 The DSC has no requirements for earthquake stability of new or existing outlet towers, bridges and ancillary works unless their failure would result in uncontrolled loss of storage or would threaten dam failure. Where the DSC has requirements each case would be treated on its merits and consistent with the requirements of Section 5.8.

5.3 Design Loadings

5.3.1 For extreme and high Consequence Category dams, obtain seismic loadings from an experienced seismologist who is familiar with the characteristics of earthquakes in Australia.

5.3.2 The following dam safety levels are required to be achieved:

Table 5.3 - Maximum Design Earthquakes

Consequence Category	Earthquake Annual Exceedance Probability (AEP)
Extreme	<1 in 10,000
High A	1 in 10,000
High B	1 in 5,000
High C	1 in 1,000
Significant	1 in 500

Notes:

1. Consequence Categories as per ANCOLD "*Guidelines on Consequence Assessment"* and DSC3A.
2. This dam safety level is to be achieved with the reservoir at Full Supply Level.
3. For extreme Consequence Category dams, the owner is to demonstrate that the design safety level is appropriate to the consequences of failure.
4. If loss of life is expected the AEP shall not exceed 1 in 5000.

The DSC may consider, on a case by case basis, any proposals by the owners of existing dams for lower dam safety levels.

5.3.3 A deterministic approach to design loadings will be considered by the DSC subject to the identification of and comprehensive analysis of all potentially active faults local to the dam.

5.4 Design Analysis for Concrete Dams

5.4.1 For extreme and high Consequence Category concrete dams, base the design on an accepted dynamic analysis method (for gravity dams the method given in the ANCOLD Guidelines for Design of Dams for Earthquake - Section 7 is acceptable) and carry out a deformation analysis such as a Newmark type analysis (Newmark 1965 and as subsequently modified).

5.4.2 For significant Consequence Category concrete dams carry out as a minimum a pseudo-static analysis.

5.5 Embankment Dams Susceptible to Liquefaction Failure

5.5.1 For all extreme, high and significant Consequence Category embankment dams determine whether the dam or foundation is potentially subject to liquefaction and report the determination to the DSC.

5.5.2 For dams subject to liquefaction the DSC will accept an established empirical approach as a basis for establishing safety. The approaches provided in the ANCOLD guidelines are acceptable to the DSC, subject to the advice given in Fell (2005).

5.6 Design Analysis for Earthfill Dams

5.6.1 For extreme, high and significant Consequence Category earthfill dams carry out a staged stability analysis based on the procedure outlined in Section 6 of the ANCOLD earthquake guidelines and summarised in the flow chart of Figure 32. For extreme and high Consequence Category dams the appropriate methodology shall be selected from initial screening through to dynamic, non-linear methods. The DSC notes the importance of well designed and constructed filters and the provision of substantial freeboard in improving the safety of dams under earthquake loads.

5.7 Design Analysis for Rockfill Dams

5.7.1 Concrete faced rockfill dams of free-draining rockfill are often designed empirically on the basis of precedent performance. The DSC will accept such a design basis. Analyse dams of rockfill that are not free-draining, in a similar manner to earthfill dams and current best practice. The DSC endorses the references listed in this document and in the ANCOLD Guidelines for Design of Dams for Earthquakes.

5.7.2 Rockfill dams that are not free draining or other rockfill dams shall be treated in a similar manner for earthfill dams.

5.8 Appurtenant Structures

5.8.1 The design of appurtenant structures where they are relevant to dam safety shall be in accordance with Section 8 of the ANCOLD Guidelines. Give particular attention to structures, mechanical components and electrical fittings on the superstructure of concrete dams. Such elements are often fragile and may be subjected to accelerations many times greater than the peak ground acceleration. Their failure may leave the dam vulnerable, especially in the case of spillway gate operating equipment.

5.9 Defensive Measures

5.9.1 For extreme, high and significant Consequence Category dams, particularly embankment dams, employ appropriate defensive measures. These are measures that are not amenable to direct quantitative analysis but which are known to significantly improve safety under seismic loading. Examples are listed in Section 5.2 & 7.2 of the ANCOLD, 1998, Guidelines.

5.10 Upstream Occurrences

5.10.1 Consider the potential for reservoir rim landslides to be triggered by earthquake and for reservoir seiche and report on a qualitative assessment of the implications for the safety of all extreme, high and significant Consequence Category dams.

5.11 Post Earthquake Procedures

5.11.1 The DSC considers that there is a considerable risk to dam safety for some time after an earthquake event. This risk may arise from the vulnerability of the dam or its foundations weakened by an earthquake and subject to post quake shock at normal reservoir level, a following flood event, the initiation of piping, the initiation of slope instability or the inability to operate the dam to the required standards.

Where analysis indicates that an extreme, high or significant Consequence Category dam will be damaged during an earthquake to an extent that makes it more vulnerable to a subsequent flood or earthquake, during the period before repairs can be completed, an analysis of safety under the subsequent event should be undertaken. The maximum magnitude of the subsequent event should be selected having regard to the overall probability of occurrence of the two events. An important consideration in such analyses is the ability to draw the reservoir down and to maintain it at a lowered level.

5.11.2 Dam owner's are required to have in place an effective Dam Safety Emergency Plan (DSEP) prepared in accordance with the DSC's guidance sheet on *Emergency Management for Dams - DSC2G.* In reference to dam owners' actions after a near field seismic event, the DSEP shall specify:

- Inspection by an experienced dams engineer;
- Reporting of the incident to the DSC;
- Visual inspection and monitoring of instrumentation from the event until stability is restored;
- Guidelines detailing procedures for managing all feasible subsequent events;
- Guidelines for remedial action;
- Requirement for drawdown of the reservoir until reviewed by appropriately expert persons;

The plan shall consider, but not be limited to the implications of:

- Loss of freeboard;
- Damage to the core or impermeable membrane;
- Operation of gates;
- Operation of outlet works;
- Liquefaction effects in the foundation;
- Major instability;
- Soil strain softening.

5.12 Summary

The DSC's aim at this time is to ensure that designers responsibly assess the safety of dams under seismic loading using the best information on loading currently available in Australia together with widely accepted methods of engineering analysis. It is recognised that earthquake safety for dams, is a complex subject, and that designers should be allowed substantial flexibility within the constraints set out in the preceding sections. It is also recognised that, in many cases, loadings other than seismic will be critical for design and that in such cases dam owners should not be required to incur the costs involved in unnecessarily sophisticated analyses.

The DSC will consider deviations from these requirements upon submission of a cogent and fully documented case. In particular, if risk assessment methodologies are used they should be in accordance with the relevant ANCOLD Guidelines.

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For any further information please contact:

NSW Dams Safety Committee
Level 3, Macquarie Tower
10 Valentine Avenue, Parramatta NSW 2150

PO Box 3720, Parramatta NSW 2124

(02) 9842 8073   (02) 9842 8071

dsc@damsafety.nsw.gov.au

ISSN 1039-821X