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Robert C. Lo
Klohn-Crippen Consultants Ltd., Canada

Earle J. Klohn
Klohn-Crippen Consultants Ltd., Canada

W. D. Liam Finn
Kagawa University, Japan

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SEISMIC DESIGN OF TAILINGS DAM
AN OVERVIEW OF ITS EVOLUTION AND NEW CHALLENGES

Robert C. Lo
Staff Consultant
Klohn-Crippen Consultants Ltd.
Richmond, B.C., Canada

Earle J. Klohn
Principal Consultant
Klohn-Crippen Consultants Ltd.
Richmond, B.C., Canada

W.D. Liam Finn
Anabuki Chair of Foundation Geodynamics
Kagawa University
Takamatsu, Japan

ABSTRACT

This paper first provides an overview of the evolution of tailings dam engineering over the years. It then highlights key factors affecting seismic performance of tailings dams: such as site seismicity, foundation and damfill geotechnical characteristics, dam design, construction, operation and decommissioning, seismic slope stability, and dam rehabilitation. Finally, it reviews some of the recent trends that lead to new challenges to the engineering profession. These challenges include: coping with heightened public concern about dam safety; balancing potential conflict between seismic and environmental requirements; and addressing issues introduced by globalisation of the mining industry. Institutional responses and technological tools available to meet these challenges are outlined.

INTRODUCTION

Tailings dams are critically important elements in the management of mine tailings for modern mines. They are permanent hydraulic structures used to contain a large volume of semi-fluid tailings and supernatant water. Over the last three decades, tailings dam engineering has evolved from largely "trial-and-error" methods to a mature, multi-disciplinary engineering endeavour. It applies sound engineering principles from a variety of disciplines related to dam and environmental engineering to achieve the objective of storing mine tailings safely and economically with minimum disturbance to the natural environment.

In this paper, the evolution of sound design of tailings dams is briefly described first. Key factors affecting seismic performance of tailings dams are then outlined. Finally, recent trends and new challenges faced by the industry regarding tailings dam engineering are reviewed and discussed.

EVOLUTION OF SEISMIC TAILINGS DAM DESIGN

As in the case of many other human developments, the progress of seismic design of tailings dams has been marred by some major dam failures with severe consequences in terms of human casualties, economic losses and environmental damages (Klohn 1995). The 1965 La Ligua earthquake of magnitude 7 to 7-1/4 in central Chile, which triggered massive tailings dam failures in the affected area, was a significant milestone. It served as a catalyst for the improvement of seismic design of tailings dams both in Chile and other major mining countries around the world.

Upstream Tailings Dam

Tailings dams of early vintage were constructed by a procedure utilising a minimum of fill placement. This was achieved by building a low starter dyke and discharging tailings from the top of the dyke until the impoundment was filled with tailings. Then a second small dyke was constructed over the deposited tailings, and the procedure was repeated so that the tailings dam rose gradually in an upstream direction, hence the name “upstream method” was coined.

Many tailings dams of this type have performed satisfactorily, albeit their failures were not uncommon even under static loading conditions. The structural weakness of this type of tailings dams was brought to the fore by the dramatic failures of the El Cobre Old and New tailings dams and numerous other smaller dams in the La Ligua earthquake (Dobry and Alvarez 1967). This event ushered in the development of the “downstream” and “centreline” methods of modern construction. It also provided an impetus for tightened Chilean government regulations on the tailings disposal by the mining industry in 1970 (Cohen and Moenne 1991) and elsewhere.

Downstream Tailings Dam

With the advent of large-scale open-pit mining operations over the last three decades, the tailings volumes produced by the mining industry increase dramatically reaching billions of tonnes per annum. To meet these huge storage demands, tailings dams have evolved into very large, critical hydraulic structures. They now rival conventional water storage dams in terms of their physical dimensions and importance to public safety and environmental integrity. Major tailings dams are reaching 150 to 200 m high, and their impoundments cover a surface area in the order of 100 km^2 with a storage volume up to the order of billions of cubic metres.

Most modern "downstream" tailings dams ("centreline" dams are a special type of downstream dams where the upstream shell is comprised of tailings deposits) are constructed in two stages. Stage I, the initial starter dam, is constructed before the mining operation starts, while Stage II involves the construction of the remainder, which usually constitutes the major portion of the tailings dam. They are designed, based on sound embankment dam engineering principles, with seismic resistance commensurate with the site seismicity. The construction of Stage II dams lasts as long as the mining operations, and is usually carried out by the mine operators. Increasingly the impoundment conditions after mine closure are dictated by the environmental and long-term land-use considerations. Unless these considerations are properly incorporated in the design, the dam's seismic resistance could potentially be compromised.

EARTHQUAKE-INDUCED TAILINGS DAM FAILURES

Our understanding of the mechanisms of seismic failures of tailings dams has benefited from the investigations and analyses of the case histories of both failed embankment and tailings dams caused by earthquakes (USCOLD 1992, 1994) as well as the overall advancement of earthquake engineering.

In simplistic terms, a tailings dam fails in an earthquake because its shearing strength along a critical failure zone reduces as the result of earthquake shaking to an extent that the remaining strength is no longer sufficient to resist the gravity loading, plus the additional inertial loading. The loss of shearing strength due to the development of seismic pore pressure often plays the key role of initiating slope instability. As the tailings dam slopes deform and slump, the retained saturated tailings, having itself been transformed to a heavy viscous fluid by earthquake shaking, begins to flow out through the dam breach in the slumped area. Once the tailings deposits within the tailings beach area, the zone separates the free pond water from the tailings dam structure, flow through the breach in the dam the free water in the pond follows. The ensuing erosion by the escaping water enlarges and deepens the dam breach and leads to further release of the stored tailings and possibly complete failure of the impoundment. Sometimes this process does not run its full course; it either leads to a partial impoundment failure or escapes a dam breach altogether. Factors affecting the failure progression include: the amount of stored supernatant water, the width of the tailings beach, the degree of saturation and characteristics of the tailings deposits adjacent to the retaining dam, the amount of slump suffered by the dam slopes, and the severity and duration of earthquake shaking. For cases which did not lead to dam failures, slumping, settlement and cracking of the tailings dam and the upstream tailings beach slope were often accompanied by the formation of sand volcanoes and water spouts on the beach (Dobry and Alvarez 1967, CRIBC-MMI 1989).

The January 14 and 15, 1978 near Izu-Oshima earthquakes in Japan demonstrated the effect of aftershocks and relative performance of upstream and downstream dams (Marcuson et al. 1979, Okusa and Anma 1980). The main shock of magnitude 7 is located about 38 km from the Mochikoshi tailings impoundment, while the largest aftershock of magnitude 5.8 is located nearby. Two upstream dams failed. The 34-m high Dam No. 1 failed totally after the main shock, while the 25-m high Dam No. 2 failed partially about 5 hours after the largest aftershock and 24 hours after the main shock. The 10-m high Dam No. 3, a downstream dam, survived both events. At El Cobre in Chile, Dam No. 4 was constructed since 1968 by the downstream method near the sites of the Old and New Dams, which failed in the 1965 La Ligua earthquake. Dam No. 4 has experienced two major earthquakes (a magnitude 7.4 event in 1971 centred also near La Ligua when the dam was about 15 m high, and a magnitude 7.5 offshore event in 1985 centred near Ports Valparaiso and San Antonio when the dam was about 45 m high). Except for some slumps at the downstream toe in 1971, and some superficial slumping of newly constructed zone in 1985, no other damages were incurred by the dam (Cohen and Moenne 1991). On the other hand, during the 1985 earthquake two poorly constructed tailings dams, Veta del Agua Dam No. 1 and Cerro Negro Dam No. 4, which were located slightly further away from the epicentre, failed and resulted in flow slides of the stored tailings (Troncoso 1989). In the United States, a 24-m high upstream-constructed tailings dam in the Tapo Canyon tailings impoundment failed during the 1994 Northridge earthquake of magnitude 6.7. The dam is located 21 km from the epicentre. Its failure led to large downstream displacements (60 and 90 m) of two sections of the dam, and the escape of stored tailings (Harder and Stewart 1996).

FACTORS AFFECTING SEISMIC DAM PERFORMANCE

Key factors affecting the seismic performance of tailings dams have been elaborated elsewhere (ICOLD 1995, Lo et al. 1995). They are briefly discussed below:

- Site seismicity assessment and design earthquake selection. Seismicity assessment has emerged as a mature discipline (Sommerville 1998), which defines both the severity and type of potential seismic events at a site (magnitude, hypocentral distance and fault mechanism) and their ground motion time-history characteristics (acceleration, velocity and displacement). Two levels of design earthquakes are generally considered: the operating basis earthquake (OBE) for maintaining normal operations; and the maximum design earthquake (MDE) for extreme conditions. Selection of appropriate design events depends on the consequences of a dam failure and the level of protection demanded by the public (ICOLD 1989a, CDA 1999).

- Foundation and damfill geotechnical characteristics. Important characteristics include foundation pore pressure, dam phreatic surface, insitu density, shear wave velocity, strength and stress-strain relation under static and seismic conditions of materials involved. In turn, these characteristics are determined by appropriate field and laboratory investigations;

- Design, construction, operation and decommissioning of tailings dam. These encompass the selection of: type, slopes and zoning of a tailings dam, design measures such as compaction and/or drainage to provide seismic resistance, construction method and level of quality control, instrumentation, operation and long-term closure conditions of the impoundment;

- Seismic slope stability. The maintenance of dam slope stability under seismic loading is critical to prevent loss of freeboard and ensuing dam breach. Understanding of potential dam failure mechanisms and simulation of dam performance by carrying out appropriate seismic stability and response analyses play an important role in this aspect (Finn 1998, 1999); and

- Dam rehabilitation. As dam deficiencies are identified, determination of the appropriate extent and method of rehabilitation has a direct bearing on the cost involved and safety enhancement achieved.

RECENT TRENDS AND NEW CHALLENGES

Heightened Public Concern

Although tailings dam engineering has made considerable progress over the last three decades, a significant number of tailings storage facilities have failed in recent years, albeit many of these failures are not related to earthquakes (Berti et al. 1985, Vick 1997, Wagener et al. 1998, MEM 1998, UNEP-OCHA 2000). These failures, which included both old and new facilities, had serious downstream impacts such as river pollution and flood and mud flows with attendant casualties and property losses. Television images, newspaper headlines and internet stories of these failures reached the general public around the world almost instantly. As a result, the public's awareness of the vulnerability of tailings dams has been heightened (UNEP-DHA 1996).

The potential real or perceived risk of an existing tailings facility to its downstream community and environment could increase with time due to the following reasons:

- Seismic hazard increase. This increase may result from new understanding of the site's seismo-tectonic setting, the discovery of new faults, or reactivation of dormant seismic activities that having relatively long recurrence intervals;

- Population increase and economic development. This trend in the area downstream of the facility could elevate the consequence of a potential dam incident or failure from a ranking of low to medium to a ranking of high to very high;

- Public intolerance of risk exposure. While objectively the physical risk exposure may remain the same, the tolerance level of the public to the involuntary risk imposed by the facility could drop due to the shift of societal attitudes and values.

Increasing Environmental Demand

Potential environmental concerns related to tailings impoundment usually arise from the actions of water and wind erosion, physical and chemical weathering processes, natural occurring and remnant process chemicals, or radioactivity. The nature and timing of release of environmental pollutants depend on the characteristics of the offending materials involved. Strategies to protect the tailings impoundment environment usually include one or more of the following (Tremblay 2000):

- Permanent submergence;
- Capping and re-vegetation; and
- Water treatment and release.

Permanent storage of supernatant water within the tailings impoundment is required for the submergence option. This option, being effective to control acid-rock drainage and almost maintenance free, is quite attractive. The requirement of water storage could be accommodated with relative ease in the design of a new facility. However, if the introduction of this requirement to an existing facility leads to uncertainty regarding the seismic dam stability, it could pose a significant challenge to the dam designers. Adoption of the capping and water treatment measures in design could reduce the extent of impoundment submergence, and lessen its impact on the dam's seismic stability.

Globalisation of Mining Industry

With the integration of the world economy, mining companies are increasingly operating in the international arena and away from their home base. This trend has gradually spread from a few major international mining companies to intermediate and junior ones. Potentially some tailings engineering practices evolved in one region may be applied to other parts of the world without a thorough evaluation of their appropriateness. A particular practice may be quite compatible with the special climatic and seismo-tectonic setting of its origin. Their indiscriminate transplant to areas of substantially different environment could lead to unexpected operational difficulties and/or poor dam performance.

Also in the vigorous pursuit of cost reduction and shorter time line of project development, other important intangible considerations, such as thoroughness in the investigation and design process and maintenance of continuity in project control, receive much less attention. The physical distance between remote project sites and design offices further curtails the designers' ability to follow closely the subtle yet important changes in site conditions and construction practices during the protracted construction years. Frequent changes of designers and even owners could only exacerbate the situation. Thus, it is not surprising for us to witness a rash of tailings incidents and/or failures in recent years, especially in developing regions where the governmental regulatory activities are playing catch up with the rapid international mining developments.

INSTITUTIONAL RESPONSES

In response to increased public demand for safe tailings facilities compatible with their surrounding environment, both the mining and engineering industries and governmental and non-government agencies have taken initiatives to improve the tailings practice. Examples of these initiatives include the increasing use of operation manuals, emergency response planning, annual reviews by designers, peer design reviews, external audits of tailings practice, etc. Mining and engineering associations have also adopted good-practice guidelines such as:

- A Guide to the Management of Tailings Facilities by the Mining Association of Canada (MAC 1998);
- Dam Safety Guidelines by the Canadian Dam Association (CDA 1999); and
- Bulletins on the design, construction and maintenance of tailings facilities by the International Commission on Large Dams including ICOLD 1982, 1989a, 1989b, 1995 and 1996.

Furthermore, government authorities at various levels have established rules and regulations to be followed by the mining companies from the initial planning and investigation of a tailings facility through its design, construction, operation and eventual decommissioning. Governmental efforts have also been augmented by those of non-government international organisations such as regional and world agencies including those providing funding support for projects in developing countries. For example, the Industry and Environment Centre of the United Nations Environment Programme and the International Council on Metals and the Environment have formed the Environmental Protection Working Group on Mining and Metallurgy (UNEP-ICM). The working group, having identified tailings issues as one of the key challenges to achieving improvements in environmental performance, has used workshops and publications to promote good environmental tailings practices since 1996 (UNEP-ICM 1997, 1999).

TECHNOLOGICAL TOOLS

Considerable advancement has been made in the technological tools used to investigate, design, analyse and rehabilitate tailings dams. Some of these advancements are highlighted below:

Geotechnical Field and Laboratory Investigations and Testings

Continued improvement and development of field insitu penetration tests and geophysical logging as well as the correlation of these test data with known case histories result in an increase in efficiency and reliability as well as decrease in cost to characterise the properties of potentially problematic natural or fill materials.

Laboratory monotonic and cyclic shear tests including triaxial compression and extension tests, and simple shear tests provide important data to evaluate the development of seismic pore pressure and stress-strain relationships in the prototype field condition. Provided that the laboratory samples preserve the characteristics of field materials, and the test conditions and stress ranges simulate the field loading conditions, these test results capture the highlights of the seismic behaviour of materials involved. Both the field and laboratory test data are then used in the analyses of the prototype dam performance under earthquake loading (Finn 1998). Among other material properties, residual strength plays an important role in evaluating the overall performance of tailings dams involving contractive, loose to medium dense materials. The theoretical and conceptual issues, the laboratory and field tests, and the case histories related to the residual strength are discussed in a recent workshop (NSF 1998), and summarised by Stark et al. (1998). Besides case studies, centrifuge tests appear to offer the next best option to study the seismic behaviour of the tailings dam prototype in a carefully controlled and monitored environment (Kutter and Balakrishnan 1999, Zeng and Rohlf 1998).

Seismic Response Analyses

Non-linear, effective-stress finite-element and finite-difference computer programs are now available to evaluate the seismic response of a tailings dam including its foundation and upstream tailings deposits (Finn et al. 1986, Finn and Yogendrakumar 1989, Finn et al. 1990, Inel and Roth 1993, Itasca 1998, Wu 2000). These analyses could capture the seismic pore pressure generation and its subsequent re-distribution and dissipation as well as large-strain embankment deformation. These analyses have been used for back-analyses of known case histories of embankment dams as well as for design studies for new dams and safety evaluation and retrofitting of existing dams. The continual advancement and application of these analyses will assist us to gain insight and confidence in evaluating the tailings dam's seismic response, especially after some of these results are verified in future as the design earthquake actually occurs at the dam sites.

Risk Assessment

Risk assessment methodology, varying from its simplest form of failure mode and effects analysis to a full-blown form of event-tree probabilistic analysis, has been applied to talings dams evaluation (Finn 1998 and Watts et al. 1999). When carried out in a comprehensive and conscientious manner, the mere process of conducting the assessment could lead to the identification of the most vulnerable areas of the tailings impoundment, and establishment of priorities for their improvements.

Measures to Enhance Safety and Mitigate Failure Consequences

Measures that could be employed to enhance the safety of an existing facility and/or to mitigate the consequences of its potential failure have undergone continual improvement (Mitchell 1988, Adalier et al. 1998). Some of these methods applicable to tailings dam rehabilitation are:

- Densification of Dam and Foundation Material - Since considerable volumes of materials requiring densification are usually involved, it will be very expensive to carry out such an undertaking. If the problematic materials are at relatively shallow depth, excavation and backfill with compacted material, dynamic compaction, and sheet piles could be considered (Klohn et al. 1982, Adalier et al. 1998, Towhata and Mizutani 1999). At depth, controlled blasting could be more cost-effective (Handford 1988).
- Drainage or Dewatering to Lower Pore Pressure - Improved drainage by installation of horizontal drains and vertical relief or dewatering wells could reduce the dam phreatic surface and/or foundation pore pressure. This measure will improve the static stability of the dam and in turn reduce the potential of earthquake-triggered slope failure (CRIBC-MMI 1989).
- Flattening Dam Slopes and/or Addition of Buttressing Berms – These conventional measures could be used alone or in combination with other measures to improve both the static and seismic dam stabilities (Hansen et al. 2000).
- Structural Reinforcement – Pre-stressed concrete piles have been used to reinforce a weak clayey silt foundation layer of Sardis Dam (Finn et al. 1998), while deep soil mixing have been used to improve the seismic resistance of a 15-30 m thick, loose sand and gravel alluvial foundation layer at Jackson Lake Dam (Ryan and Jasperse 1989).

On occasions where the cost of dam rehabilitation is prohibitive, it may be possible to consider the option of accepting the risk of potential impoundment failure. This should be considered as the last resort, and only if no loss of life is anticipated, and the environmental impact is minimal. Tailings runout and flood inundation studies should be carried out to map the extent of potentially vulnerable areas downstream. Engineering protective measures against downstream damages from debris flow and flood should be considered as part of the overall remedial scheme.

CONCLUSIONS

As tailings dams grow in physical size to meet the tailings storage need of modern mines of large production capacity, their impact on the public safety and environment also increases in severity. Concurrently the tailings dam engineering, including the seismic design aspect, has matured by learning from past failures and adopting sound embankment-dam design and construction practice. However, safe tailings storage facilities require continual efforts and vigilance of the institutions and individuals involved in their design, construction and maintenance. In the near future our main challenge probably lies in providing cost-effective means to evaluate and rehabilitate existing facilities with seismic deficiencies. The additional environmental constraints present in some cases could make this challenge even more demanding.

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