Reliability Engineering and Resilience 4-1 (2022) 01-30

Contents lists available at **RER**

Reliability Engineering and Resilience

Journal homepage: www.rengrj.com

Earth Dam Behavior under Earthquake Movements- An Overview

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https://doi.org/10.22115/RER.2022.340458.1046

ARTICLE INFO

Article history:
Received: 02 May 2022
Revised: 19 July 2022
Accepted: 28 July 2022

Keywords:
Earth dam;
Earthquake movements;
An overview.

ABSTRACT

In this review article, we examine the behavior of earthen dams under earthquake movements. Earthen dams perform satisfactorily when exposed to strong earthquakes. Their performance is usually related to the nature of the soil used for the structure. Most well-constructed earthen dams can significantly vibrate the earthquake without damaging effects. Dams made of compacted clay materials on clay foundations or bedrock withstood strong ground movement. Compared to older embankments built on sandy materials or of sand or silt with inefficient density and tailings dams, all of them showed almost some instances of failure, which was initially due to the liquefaction capability of these materials. They are considered a type of hydraulic structure in this period, and tailings dams are the most dangerous types of earth dams. The more accurate and durable equipment and tools are used during the construction and operation of the dam, the minor deformation is created in the dam, and the more controllable it becomes. Utilizing up-to-date knowledge and benefiting from the construction and maintenance experiences of the dam can help the optimal management of the dam during construction and operation. The main finding from this study is earth dams have better flexibility to accept the dynamic load due to earthquake force than concrete dams.

How to cite this article: Ghiasi VM, Azami M. Earth Dam Behavior under Earthquake Movements- An Overview. Reliab. Eng. Resil. 2022;4(1):1–30. https://doi.org/10.22115/rer.2022.340458.1046

1. Introduction

Earth and rockfill dams are important colossal structures. The initial materials used in construction of these dams include natural materials such as earth or rock [1–4]. One of the recommendations of the International Commission on Large Dams is to constantly control the safety and sustainability of dams during construction and exploitation [5–10]. In this section, past research on the behavior of earth dams under earthquake movements is reviewed. In October 2000, the American Dams Association published performance observations of earthquake damages dams. Since then, several earthquakes, including three records with a magnitude of 8 and higher, have been applied to some dams. The most important events are as follows.

- On October 6, 2000, in the western Tutor area of Japan, with a magnitude of 7.6

- On January 16, 2001, in the Bahuj region of India, with a magnitude of 7.7

- On October 23, 2004, in the central region of Niigata, Japan, a magnitude of 6.6

- On March 35, 2007, in the Tutu Hato area of Japan, with a magnitude of 9.6

- On June 14, 2008, in the Iwata Miyaji area of Nairko, Japan, with a magnitude of 9.6 - On May 12, 2008, in the Wenchuan region of China, with a magnitude of 8

- January 2009 in Costa Rica with a magnitude of 3.6 - February 2010 in Chile with a magnitude of 8.8 - March 2011 in the Tohono region of Japan with a magnitude of 9

These events provided important additional information regarding the seismic performance of dams. Historically, few dams have been significantly damaged by earthquakes. On a worldwide basis, only about a several dams are known to have failed completely as the result of an earthquake. These dams were primarily tailings or hydraulic fill dams, or relatively old, small, earthfill embankments of perhaps inadequate design.This report is a continuation of previous reports and includes about two thousand articles published up to 1992. This set includes 1 case study of dams under moderate to strong earthquakes. An introduction to the two thousand papers published in the following paragraphs will explain the seismic performance of dams under several recent earthquakes [11].

Historically, a small number of dams have been severely damaged by earthquakes. The earthquake has destroyed only about a dozen dams in the world. These were tailings dams (due to landfills) or relatively old, small hydraulic dams and embankments with poor design. Also, about twelve other dams were severely damaged by the earthquake, and embankments or concrete weight dams with significant heights were in this group. Several earthen dams also experienced near-total rupture. More than 91,000 dams dot the nation—and roughly 15,500 of them could cause fatalities if they failed, according to the National Inventory of Dams. Most of these dams were built many decades ago. By 2025, 70 percent of them will be more than a half century old, according to the American Society of Civil Engineers. About 1 in 6 dams has a high hazard potential.These 15,500 dams are deemed so crucial that if they were to fail, it would likely cause loss of life and heavy economic damage. Both of the dams near Midland, Michigan

had this rating. The National Inventory of Dams lists condition information for nearly 80 percent of high-hazard potential dams, meaning that their failure would result in at least one death. More than 2,330 of these high-hazard dams need repairs, some 15 percent of all dams in this hazard category. But data remain spottier for dams of other hazard potentials, such as significant or low hazard. More than 8,000 dams are over 90 years old. Old dams are not necessarily unsafe, but they need to be maintained for integrity. The dams near Midland were built in the 1920s and had a history of safety concerns [12] Today in the United States, according to the U.S. Army Institute 2010, there are more than 6,269 dams larger than 155 meters, 1666 dams larger than 330 meters, and more than 469 dams larger than 660 meters. According to these statistics, and even the number of dams in the world, of which American dams, the number of failures and endangerment of dam structures is very low. Except for a few known dams, the rest were designed according to the earthquake according to the Seismic Parameters Code of the dams in 1999, which were not tested under seismic force by the American Large Dams Association small number of dams experienced significant damage. The current report includes the historic dams of Aratozawa, Kononto Viejo, Ishibuchi, and shape, which survived the design quake and suffered no damage. An updated list of dams that have experienced significant earthquakes is presented in Table 1. This table includes the earthquake's location, the main seismic parameters, the size and type of the dam, the distance to the epicenter, and the severity of the damage reported. Table 2 also describes the terms used in Table 1. [13,14].

This article will review the behaviors of earthen dams under earthquake seismicity in different countries.

Table 1
Dams that have experienced significant earthquakes [14].

Damage Rate	Space (Km)	The Magnitude Of The Earthquake Richter Or Merkali	Earthquake History			The Name Of The Earthquake	Earthquake Depth Font Ft	Type	Country	Dam Name
Break	180	7	1888	August	31	Carlston	-	E	Georgia	Augusta
Low	64	-	1894	July	12	San Francisco	-	M	California	Stephenson Creek
Low	-	8/3	1906	April	19	San Francisco	28	E	California	Osan Andreas
Low	-	8/3	1906	April	19	San Francisco	96	E	California	San Andreas
Medium	-21	8/3	1906	April	19	San Francisco	28	E	California	Lake Ranch
Harmless	3/3	8/3	1906	April	19	San Francisco	45	E	California	Bear Gulch
Harmless	3/3	8/3	1906	April	19	San Francisco	102	E	California	Pilarcttos
Medium	0/1	8/3	1906	April	19	San Francisco	-	E	California	Saratoga
Medium	0/2	8/3	1906	April	19	San Francisco	28	E	California	U.Howell
Medium	0/3	8/3	1906	April	19	San Francisco	36	E	California	L.Howell
Harmless	2	8/3	1906	April	19	San Francisco	45	E	California	Crocker
Harmless	3	8/3	1906	April	19	San Francisco	47	E	California	Crocker
Harmless	4/4	8/3	1906	April	19	San Francisco	50	E	California	More Dale
Medium	0	8/3	1906	April	19	San Francisco	75	E	California	U.Crystal Springs
Harmless	0/2	8/3	1906	April	19	San Francisco	127	Ga	California	L.Crystal Springs
Harmless	60	8/3	1906	April	19	San Francisco	64	Ga	California	Searsville
Harmless	6/4	8/3	1906	April	19	San Francisco	15	E	California	Magenta
Harmless	8	8/3	1906	April	19	San Francisco	28	E	California	Belvedere
Harmless	8	8/3	1906	April	19	San Francisco	17	E	California	U.Molnt Baslan
Harmless	45/2	8/3	1906	April	19	San Francisco	28	E	California	Lagunitas
Harmless	19/2	8/3	1906	April	19	San Francisco	50	E	California	Cowell

Table 2
Terms used in Table 1 [14].

CA	Concrete Arch
GA	Concrete Gravity Arch
MA	Multiple Concrete Arch
CAB	Concrete Arch Buttress
CG	Concrete Gravity
CGB	Concrete Gravity Buttress
M	Masonry
E	Earthfall
COMP	Composite (fill/concrete)
ECARD	Earth Core Rockfill
CFRD	Concrete Face Rockfill
HF	Hydraulic Fill
T	Tailings

2. Operation of earth dams until September 2012

At 12.30 pm on October 6, 2000, a magnitude 6.70 earthquake at a depth of 11.30 km with a latitude of 35 degrees and 16.50 minutes north longitude and longitude, according to the Office of the President of the West Totori Region of Japan. It happened at 133 degrees and 21 minutes east. Fortunately, no one was killed, and only 132 people were injured; 28 houses were destroyed, 82 houses were partially destroyed, and 5050 houses were slightly damaged. Many aftershocks occurred, the most important of which was a 5-magnitude aftershock and three aftershocks with a magnitude greater than 4. After the earthquake, 180 dams were inspected, and 18 small earth dams were damaged. In the case of concrete dams, the three weight dams performed very well. On October 23, 2004, a magnitude 80.6 earthquake shook the Chennosto region of Japan, killing at least 40 people and causing landslides on artificial embankments. Brought. In this earthquake, the Japan Accelerometer Network reported the maximum acceleration equal to 1.50 to 1.80 times the acceleration of the earth's gravity. A large number of aftershocks were recorded within a week after the earthquake. Several earthen dams used for irrigation and hydroelectric use were damaged during the earthquake. According to Yasuda et al., In 2004, during the earthquake, the dam was empty of water due to the dry season of the irrigation service area. But in the case of hydroelectric dams, including the Yamamoto Sen Shin Yamamoto and Asagawara, which were located 65 and 22 kilometers from the epicenter, they suffered moderate and no threatening damage. In this incident, eight irrigation dams were monitored and inspected. [15,16] On June 14, 2008, a magnitude 6.90 earthquake shook the region of Iwata Miyaji Nabrico in northern Japan. The magnitude of the earthquake was so great

that an earthquake with a magnitude of 4 times the acceleration of the earth was produced. Twenty-three people were killed, 200 were injured, and 2,000 buildings were damaged. The quake occurred in a sparsely populated mountainous area, so the number of buildings reported was small compared to the extremely high acceleration mentioned. However, several landslides and ruptures of embankments were observed and caused the closure of mountain roads. One hundred thirty-four dams were inspected, and 12 dams were reported damaged, but the damage was not very serious. According to Makdisi et al., In 2008, the 81-meter-high Aratozova Dam suffered only minor damage at a maximum acceleration of 1.03 grams [17]. A heavy landslide occurred inside the dam on the northern front, causing water to overflow from the overflow. The Ishibuchi Dam shook violently with the concrete surface but suffered minimal damage. The Masawata Dam, 38 meters high with a canopy width of 10 meters and a base width of 223 meters, faced low algal growth on the slope of the reservoir and low water volume during the earthquake. This dam was faced with 1.55-meter subsidence in the crown of the dam and the upper part. On both sides of the crown of the dam, the installed iron guard was bent and deviated from the axis, and transverse cracks were observed in the floor of the crown of the dam. According to a 2008 report by Kayen et al. 2008, A meeting between the overflow and the adjacent dam was observed to be between 10 and 20 cm and irregular [18]. Koda Dam, with a height of 47.50 meters in the northwestern region of Miyaji, located on the bed of the Nagasaki River, an earthen dam with a clay core and pebble shells, was completed in 2005. The upstream slope is 2.8 to 1, and the downstream slope is 2 to 1. The clay core is 10 meters wide at the crown of the dam and 46.66 meters at the base, and the dam was located 32 kilometers from the epicenter. The severity of the damage was reported to be minimal, and the maximum subsidence in the crown of the dam was 1.25 to 2.50 cm, and the downstream was 5 cm, but no cracks were observed on the surface or floor of the crown. According to a report by Panakuchi et al. Also, in 2008, Kayen et al. Leaked 90 liters per minute before the earthquake to 190 liters per minute after the quake, which almost doubled [18,19].

On January 8, 2009, a magnitude 6.10 earthquake shook Costa Rica, with the epicenter about 20 miles (20 km) northwest of San Jose. Landslide damage was reported on roads, bridges, and houses. The death toll was 34, and many were injured. The two dams (IKCE) were located near the epicenter. Noro Dam No. 2, with a height of 12 meters and a crown cell of 566.66 meters, was 11.50 kilometers from the epicenter. The damage related to this earthquake included longitudinal cracks in the crown of the Dam and Kippers dam with a height of 33.33 meters shook with a magnitude of 0.45 g, while the distance from the dam to the epicenter was only 10.30 km. The damage to this dam was only longitudinal cracks in the crown of the dam. Both barriers were maintained and repaired immediately after the earthquake. According to Clement and Polanos, in 2009, the first effects observed after the earthquake in the mentioned projects were water turbidity. [20] On May 12, 2008, a magnitude 8.0 earthquake shook Sichuan Province in southwestern China. A 270-kilometer fault caused the quake. The duration of the earthquake was exactly 2 minutes; the site was located on deep alluvial deposits. The maximum acceleration is estimated by observing the damages, injuries, and the distance to the faults. According to Babbitt and Charnwood, 80,000 people were killed in 2000. In this earthquake, 40 dams were broken, and 331 dams were in a dangerous situation. Ninety-five of the damaged reservoirs were small earth dams. With a concrete design of Zippo Po concrete surface and a height of 170.66

meters in 7 km of faults, the dam withstood a maximum acceleration equal to 50 to 40% of the earth's gravity acceleration. The crown sank 1 meter, and small parts of the concrete surface were damaged. According to Babbitt and Charavood, in 2009, the Seiko Sand, with a height of 111.166 meters with a central core, experienced an acceleration of 0.50 grams, and the crown met with a sitting of 22.86 cm [21].

At 3:33 am local time on May 27, 2010, a magnitude 8.80 earthquake shook central Chile. The epicenter was reported just 8 kilometers off the coast of Chile. The quake affected an area of 80,000 square meters for 100 seconds, while the maximum ground acceleration was 0.60 grams. Five hundred twenty-one people were killed, and more than half of those killed were due to the tsunami caused by the earthquake. More than 800,000 people were injured or homeless, more than 333,000 buildings were damaged to varying degrees, and at least 16 dams were shaken, but there were no reports of ruptures, only cellular and transverse cracks caused by the quake. According to Nogwara 2010 and Barry et al. In 2010, the Kubuntu Viejo Dam, or a 34-meter-high earthen dam, suffered no damage while experiencing an acceleration of 0.38 grams. No scaling was observed upstream of Guyano Dam, and cracks in the crown without liquefaction [22].

On March 11, 2011, Japan's Tohono earthquake near the North Sea caused a tsunami and caused extensive damage. On April 8, 2011, 12731 people were killed, and 13706 people were missing. 216818 buildings were also damaged or destroyed. Immediately after the earthquake, Fukushima Nuclear Power Plant No. 1 suffered severe damage, and on March 31, more than 400 dams were inspected. In general, the performance of the dams was good concerning the minimum cracks. According to Yamaguchi et al., In 2012, the crown of the Surikawa Dam, which was completed in 2006 at the height of 58 meters, had an 18-centimeter leak, and oblique cracks occurred near the dam's supports and in its crown. The leak rate had risen from 18 gallons per minute to 25 gallons per minute. The amount of acceleration measured in the foundation was 0.11 g, which was increased by 0.47 g in the crown of the dam. According to Yamaguchi, in 2012, the cracks had expanded to a depth of 33 cm. Kojima Dam, with a height of 26.50 meters and a central core built-in 1955, also experienced accelerations of 0.27 grams and 0.50 grams in the foundation and crown of the dam, while the maximum subsidence of 16 cm was achieved in the dam. And subsidence was reported from 5 to 110 gallons per minute, and oblique cracks in the dam crown with a width of 2.54 cm. According to Yamaguchi et al., In 2012, the Minamikawa pebble dam with 21.33 meters leaked from 5 to 23 gallons per minute after the earthquake, observed cracks in the asphalt surface, and the maximum subsidence in the crown of the dam were equal to 10. The horizontal acceleration at the dam crown was 1.30 Gzm, and the acceleration at the foundation was 0.27 Gzm, measured one kilometer from the Main Dam. Yamaguchi et al. Analyzed subsidence and increased leakage in this and other dams and stated that a long magnitude nine magnitude earthquake had significant effects. An exception to the good performance of the dams was the agricultural Fuji Loma One document which failed and killed eight people. The dam was built in 1949 with a height of 20 meters and a length of 145 meters, located 80 km from the fault. According to initial reports by Harder et al., This analysis was also endorsed by the panel in 2012 [19].

3. Operation of earth dams before 2000

The San Francisco earthquake in 1906 with a magnitude of 7.90 on 30 medium-sized earth dams within a radius of 50 km from the center of the fault, while 15 dams were located 5 km from the fault; in this earthquake, the maximum number of people died. They escaped unscathed, and the damage was minimal. According to Seyed et al. In 1978, the main reason for the dams' good performance under the earthquake was the good density of the clay. (Syed et al., 1978) In Japan, in 1923, the Kanto earthquake occurred with a magnitude of 7.90, and this was the first serious damage to dams that were reported. Ono Dam, with a height of 41 meters, suffered several cracks, so that in the clay part, the length of the cracks had reached 24 meters. The length of these cracks was 66 meters, and their width was 26 centimeters. The dam subsided by about 33 cm and local landslides occurred about 20 m downstream of the dam on the slope to the heel of the dam, which was reported by Seyed et al. In 1978 [23]. Several reports of moderate damage to earth dams due to the 7.30 magnitude earthquake in Corn County, California, were also reported by Syed et al. In 1978. Also, in 1978, Seyed and his colleagues stated that the Colonna Dam, with a height of 6.66 meters, was severely damaged by the 1964 Alaska earthquake, and the magnitude of the earthquake was 9.20, which led to the destruction of the dam. Seyed and his colleagues surveyed the Fernand Dam in 1978. The dam under the 1971 earthquake prompted engineers to study more seriously. Van Norman's upper and lower dams are located in an urban area. The Van Norsen Downstream Dam, sometimes called the San Fernando Downstream Dam, was 27 meters high and experienced liquefaction under an earthquake, breaking the embankment slope. The overflow from the dam crown caused the loss of 70,000 dwellings, while the volume of water inside the dam reservoir was relatively low during the earthquake due to the dry season. According to Syed et al., In 1978, the Van Norman Upper Dam was also severely damaged. The failure of the Lower San Fernando Dam was an important step in the construction of the dam, which involved the minds of engineers in dam safety during the earthquake, and researchers tried to simulate the dam and use numerical models and dynamic analysis using the software.

Another important event considered was the 1985 earthquake in Mexico with a magnitude of 8 [23]. During the earthquake, two dams named Lavilina or 66 meters high, and Inkhayrnilou Dam, with 161.66 meters, were shaken. According to Parav and Campus Bita, in 1986, the two dams were severely damaged. Still, within ten years between 1975 and 1985, the dams were under five earthquakes with a maximum magnitude of 7.20 on the Richter scale, causing cumulative subsidence caused by the quakes to be one percent higher. Importantly, both Mexican dams experienced small, measurable permanent deformations with relatively low-intensity earthquakes over ten years [24]. Two moderate earthquakes also occurred in 1987 in New Zealand and the United States, during which the 6.3 magnitude earthquake hit the Manhattan Dam at the height of 86 meters. A magnitude 6.0 earthquake also struck several dams in the Los Angeles area, with [25] that the quake was very strong. (October 17, 1989) A magnitude 6.90 earthquake shook 12 dams near the main fault line. More than 100 dams of different sizes, most earthen, were located within 100 km of the fault during the earthquake, which showed good performance. According to Paraw et al. In 1989, these events emphasized the need to pay attention to the maximum ground acceleration during an earthquake when designing dams in seismic areas. The Lomaprina Tonsil Dam, on October 17, 1989, demonstrated its ability to

withstand earthquakes that lasted longer than an earthquake. It should be noted that most dams, due to the previous drought years, had relatively little water storage of about 10 to 50% of their capacity in terms of rainfall. On the other hand, it should be noted that the dynamic forces caused by water in the reservoir have a greater impact on concrete dams than soil, although the water capacity is also reduced [24]. Good performance has also been reported in Australia. The dam, with a height of 67 meters and a crown length of 232 meters, was built between 1950 and 1951. This dam was about 610 meters away from the Andreas fault, and the epicenter of the earthquake was located at a distance of 12.50 km from the dam, and the maximum acceleration was reported to be 0.70 g. The amount of water behind the dam was half the dam's height. The maximum subsidence in the crown of the dam was 85.40 cm, and the horizontal movement of the crown was 33.55 cm. Cellular cracks were seen on the upstream slope of the dam with a width of 31 cm, and the depth of the cracks was about 4.27 meters, which were present in both supports. Due to the low density in the dam body, oblique cracks and separation of the overflow structure from the dam body were observed. A 9-meter downward sloping crack was also seen in the left abutment, which may have been due to the soft, thin soil of the bed, as well as aerated and scaly bedrocks. According to a report by Roda et al. In 1990, poor density and soft soil were cited as the main causes in both cases. The 85 cm subsidence was reasonable because the seismic design for the 8.3 magnitude earthquake included a 3 m subsidence, but the presence of cracks in the abutments and upstream was not seen in the seismic prediction. On July 16, 1990, an earthquake measuring 7.7 on the Richter scale shook the Philippines [26]. The quake caused a maximum acceleration of 6.0 g and 0.65 g in the Ampoklau Dam. The dam was 130 meters high, which was the central core of clay. There are also other dams such as Binga Dam with a height of 102 meters with a central clay core and compacted gravel shells, Masi Wei Dam with a height of 25 meters with a clay core and conglomerate and sedimentary gravel shells, and Pantababangan Dam with a height of 107 meters with a core. Clay and pebble conglomerate and sedimentary crusts were also located in the seismic zone. According to the American Dam Association in 2000, the overall performance of the dams was good, but there were only two drawbacks. At the left end of Amirklato Dam and near the overflow wall upstream, there was a movement of 50 cm, which caused the clay blanket to slip on the support, which was used to control leakage. Cracks up to 60 cm wide and 90 m long were also observed in Binga Dam in the middle of the dam and its crown. The cracks increased with the evacuation of the reservoir a few days after the earthquake. The pebbled area of Masi Vey Dam was liquefied due to sedimentary foundation and subsequently damaged [27].

An earthquake measuring 6.70 on the Richter scale shook the northern center of the Fernando Valley on January 17, 1994. The quake was important for assessing the seismic performance and damage level of buildings and bridges and the performance and vulnerability of dams for two reasons. First, the earthquake was based on tectonic movements in the California fault, which was very interesting and important for engineers and geologists. Secondly, it was an important event in the San Fernando Valley after 25 years. The first earthquake in 1971 had a magnitude of 6.60, damaging a large number of dams, and the Man Fernando Dam, or Van Norman's Lower Dam, was reported to be nearing total failure. In any case, the earthquake shook the earth. These dams often shook in 1971. As a result of the North Rich earthquake, 11 earth dams and pebbles have experienced landslides and cracks at night. However, after the 1971 earthquake, most dams

were designed for the maximum possible earthquake, and the dam's free depth increased. However, after the 1971 earthquake, most dams were designed for the maximum possible earthquake, and the dam's free depth increased. One of the major dams in the North Ridge earthquake was the San Fernando Dam, shaken again.

It should be noted that the dam was no longer drained after the 1971 earthquake and was used only to control floods but was shaken for the second time. In the second earthquake, the dam had cracks 5 to 8 cm wide, and the length of the cracks was about 30 to 60 meters. Some of these cracks had a depth of 1.50 meters. According to Bardet and Davis, in 1996, there was sand boiling upstream of the dam. Also, the maximum crown subsidence and the maximum horizontal displacement of the dam upstream had reached 20 and 10 cm, respectively. The 25-meter-high Van Norman Dam was also damaged in 1971 and had not been drained for years until the next earthquake. After the second earthquake, transverse cracks were observed in the right abutment downstream of this dam. Cracks were also created on the left side of the support, 18 meters long and 5 to 8 centimeters wide. According to Bardet and Davis in 1996, the crown was about 74 cm long, and the horizontal deformation equal to 15 cm was reported upstream. The Los Angeles Dam, 40 meters high, was located between two empty dams after the 1971 earthquake. In the second earthquake, the dam had subsidence of 14 cm in the maximum intermediate section, and its asphalt surface cracked. At the same time, the horizontal movement in the crown, according to a report by Bardet et al. In 1996, was about 8 cm. North Ridge earthquake caused minor damage due to transverse cracks and subsidence in the lower Franklin Dam "with a height of 31 meters, Santa Felicia Dam" with a height of 65 meters, Sycamore Valley Dam with a height of 12 meters, School Hose Dam in the Diriz River area with a height of 50 / 11 meters, Koo Gasol Dam with a height of 82 meters, Porter State Dam with a height of 12 meters, and Rubio River Dam with a height of 19.50 meters. Like the Loma Prieta earthquake, the North Ridge earthquake once again showed how good and acceptable the seismic performance and safety of dams designed for severe earthquakes were [28].

On January 17, 1995, an earthquake measuring 6.90 on the Richter scale struck 20 km southwest of Kuwait. Another name for this earthquake is Hugokun Nanbo. It was a very populous city with a population of about 1.50 million. The release of energy was similar to the Omaprita earthquake fault. The length of the active fault was about 30 to 50 km. More than 5,300 people were killed and 27,000 injured. The quake damaged vital arteries of buildings, roads, and bridges. Small earthen dams had a great impact at the earthquake site, but there were about 50 dams larger than 12 meters in height, 50 kilometers from the epicenter. According to Tamura et al. In 1997, as well as Pushida et al. In 1999, about half of the dams larger than 13 m were homogeneous earthen dams or gravel dams. Three small earth dams belonging to the Coyote River were located at the epicenter. The epicenter was reported below the ground. However, no tsunami alert was issued. Another small earthen dam, the Nikto Dam, was located near the site of a large earthquake that completely collapsed. Coyote reservoirs were completely low when the quake struck. A post-earthquake exploration report by the U.S. Army Corps of Engineers found that the dams were about 70 meters long, 7.50 to 10 meters high, with slopes of about 2: 1 (horizontal to vertical). They were made from a somewhat sticky mixture in a range of sand,

gravel, and silt, with some clay and a fine-grained curve and concrete surface. The taller and medium embankments of the Quinoa complex experienced massive and destructive landslide fractures downstream of the dam. However, the dam reservoir was not loaded. Traces of runoff were not found among the debris after the failure; the downstream embankment suffered from a lack of strength and severe landslides. The relatively non-resilient structures next to the site and a cemetery, located about 90 meters above the reservoir, did not suffer much damage as other sites just a few kilometers away. Only about 10 percent of the tombstones were overturned. The Kuyonen Reservoir structure, a relatively small cylindrical reinforced concrete tower, experienced little foundation movement and rotation. The tower still looks usable.

These three embankments provide a rare example of seismic damage to earth dams at the low reservoir and relatively low vibration levels. Damage was limited to earthen dams in the Kobe earthquake. Tokyo Dam A regional earthen dam 34 m high, about 10 km from the epicenter, experienced moderate cracking at the dam crown near both supports. One of these cracks had stretched to the core but was confined to the free-range water depth. The Kitamaya Dam was a 34-meter-high earthen dam made of crushed granite with a chimney drain, about 31 km from the epicenter. The dam was faced with a shallow surface slip on the upstream slope. No other damage was suspected in earthen dams higher than 12 meters. In any case, smaller earthen dams suffered various forms of damage such as longitudinal cracking, cross-cracking, subsidence, deformation of the dam body, and complete failure. The limited damage to earthen dams could be partly explained by an overall assessment of the maximum acceleration at the dam site, approximately twenty-two percent of the ground gravity acceleration in the bedrock section [29–32]. On September 21, 1999, an earthquake measuring 7.60 on the Richter scale shook the mountainous region of eastern Taiwan, Taichang, and Nantou. The quake affected the Chalangpoo Fault, significant north-northeast to south-southeast compressive fracture that tilted about 30 degrees east. About 2,400 people were killed and 10,000 injured, 100,000 buildings were destroyed, and another 7,500 were severely damaged. The fault failure was about 80 km long. There were several dams in the area affected by the Chi-Chi earthquake, such as the Tachia River Dam, the Mingtan Dam, and the Sun River Dam. According to Charlewood, in 1999, several medium-sized earthen dams underwent some subsidence and superficial cracking. In any case, they did not leak, but they did not work satisfactorily. Shuichi Dam is an earthen dam with a clay body and a central concrete core wall. The dam was built by the Japanese in 1934 and had a height of about 29 meters and a crown length of about 366 meters. The estimated acceleration at the dam site was 0.30 g, and the canopy and upper part of the dam experienced longitudinal cracks from 1.25 cm to 5 cm wide and 90 m to 300 m long. The downhill slope sat about 12 cm. The dam's employer, Taiwan Power Company, immediately filled the cracks with asphalt to prevent rainwater from seeping in and lowered the reservoir water level by about 4 meters as a precaution. Toshi Dam had a design similar to Shupichi, with a height of 18.66 meters and a crown length of 165 meters; this dam was built around the same time as Shuichi Dam. Small cracks in the dam, 15 to 50 cm, and crown subsidence of about 28 cm were reported at the dam site [33].

4. Four recent case reports of earthquake-affected dams

4.1. Aratozawa Dam, Japan

The Aranozawa Dam was hit by the largest earthquake acceleration of 1.03 G during the Iwata-Miyagi-Niriko earthquake in Japan on June 14, 2008, with only small damage. According to Kayen et al., in 2008, in the form of a landslide, most of the slope slipped into the north arm of the reservoir, causing a wave to form and the water level to rise more than the outlet, but the wave reached the top of the dam [18].

4.1.1. Aratozawa Dam

This dam is 74 meters high and is of gravel type. The upstream slope of this dam is 1 to 2.7, and the downstream slope is 2 to 1 (Figure 1). According to Amachi and Tahara in 2001, the crown of the dam is 10 meters wide and 414 meters long. The reservoir volume of this dam is 3.55 million cubic meters. This dam is built on a rock. Construction of the dam reservoir was completed in 1991. The dam started operating in 1998. The dam is built on the Ny Hazama River in Miyagi and has a storage capacity of 14,139 million cubic meters of water. The objectives of the flood control reservoir were to generate hydroelectric power and rinse and drain. The Ministry of Agriculture, Forestry, and Fisheries own the dam [55]

Fig. 1. View of the earthen Dam from the left support [18].

4.1.2. Earthquake

According to Midorikawa et al. In 2008, the Iwata-Miyagi-Nairiko earthquake 2008 (magnitude 6.9) shook northern Japan. During this earthquake, many records of strong earth movements were recorded, which included a maximum vertical acceleration of 44. About 23 people died or went missing, 450 were injured, and about 2,000 homes were damaged. The quake occurred in a

small part of the foothills, and the damage was very small compared to the intensity of the recorded earthquake. However, many landslides and sloping fractures caused extensive damage to roads and people living in mountainous areas. The epicenter was reported below the Pacific Ocean floor. However, no tsunami alert was issued. The epicenter was reported below the Pacific Ocean floor. The quake indicates that at the top of the Okhotsk plate at the top of the Pacific plate at a depth of approximately 80 km, the pressure and kinetic force were shallow. The incomplete rupture of the fault was on a low slope and inclined to the west. The focal depth was about 8 km [32]. 4-1-3: Seismic dam performance.

When the earthquake occurred, the water level inside the reservoir was 6 meters lower than the dam overflow. The distance from the dam to the epicenter was 15 km. According to Omachi in 2011, Table 3 shows the maximum acceleration recorded for the three main components of the dam at the time of the earthquake [34].

Table 3
Recorded maximum acceleration for the three main components of the Aratozawa Dam during an earthquake [34].

location	Height(meters)	transverse	longitudinal	vertical
Crown	278/5	./54 g	./49 g	0/63 g
Middle core	250	./55 g	./49 g	./48 g
Low calorie	203/7	1 / .3 g	./92 g	./70 g

The clay core settled along the dam axis up to 400 mm, and the rock crust up to a maximum of 200 mm. According to Tanny et al., As can be seen in Figure 2, the gravel shell and core placement have caused a general inward rotation in the direction of the midline of the dam. According to Figure 3, some of the columns have failed irregularly and without a definite rule. 200 mm steps in the series remain constant [35]

Fig. 2. Showing the crown of the Eratozawa Dam and the failures and deviations of historical monuments [19].

Fig. 3. 10 cm embankment in the overflow of the Eratozawa Dam [35].

Figure 4 shows how the core sits at the top of the pipe of one of the subsidence measuring devices used in one of the depots near the center of the dam crown. According to a report by Yamaguchi et al. In 2008, as shown in the figure, the pipe is about 27 cm above the dam crown. The tube is about 13 cm down due to dynamic subsidence in the crown. Otherwise, it would be separated from the surface of the crown. This event caused the pipe to come out of the manhole cover, the pipes were circular 5 meters, and the devices were 74 meters in line with the dam's height [35].

Fig. 4. Tachometer [35].

The upstream shell had a lateral deformation of 24 to 43 mm towards the tank. Despite the deformation, no apparent trace of damage was seen in the rocks placed around the upstream and downstream of the reservoir (see Figure 1). Blocks have been seen between the upstream wall and the deviation and the small opening caused by the earthquake at the junction of the gallery. The gallery was completely dry before the earthquake. Leakage measured after the earthquake was reduced, as was usually the case with other earthquake-affected dams. In 2011, Ahamachi analyzed data on strong earthquake movements due to the original shock and data obtained, including 185 aftershocks. The results show that the large strains due to the strongest displacement and sheer velocity of the wave and the shear modulus of the core components are reduced and recovered over time. The same calculations were made on the Lexington Dam data,

according to a 1991 study by McDissy et al. and Mejia et al. According to a 2011 report by Ahamachi and Tahara, the strain in this case also significantly increased the pore pressure in the core. In the barometers of the lower part of the nucleus, about 42% of the increase in pore pressure was created in one day, and the rest within three months had disappeared [17,34–36].

5. Performance of structural accessories

Partial cracks in the retaining wall as part of the overflow are shown in Figure 5. This crack is the result of earthquakes. According to a 2008 report by Kayen et al. [18].

Figure 6 shows the damaged areas of the road in the direction of the cracks, and these cracks only show the damage to the structural members [18].

Fig. 5. Cracks in the retaining wall of the Eratozawa Dam [18].

Fig. 6. The aerial photo shows three areas of cracking on the road. Overflow wall cracking shown in Figure 5 occurred below the right arrow [18].

5.1. Landslide in the tank

The total volume of the massive landslide is estimated at 50 million cubic meters, of which about 1.5 million cubic meters are in the reservoir (see Figure 7). The landslide was about 1.3 km long and 0.8 km wide. However, the slope was very gentle, about 3 to 4 degrees, and the soil mass shifted by 200 to 500 meters. During the earthquake, the lake's height increased by 2.4 m due to landslides and some tectonic deformations (from 26875 to 270/9). In 2008, Kayen et al. [18] Stated that 3.5 km of the dam access road had been closed by an earthquake.

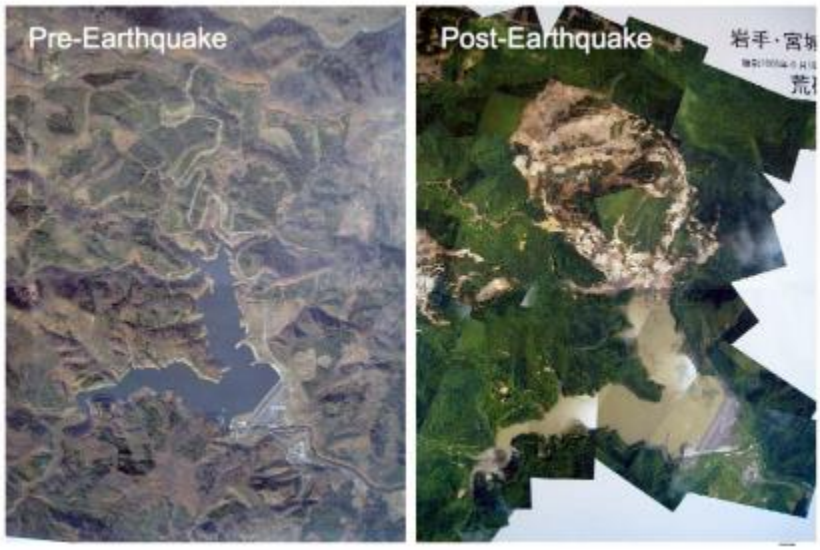

Fig. 7. Landslide inside the Eratozawa Dam reservoir [18].

Aratozawa Dam and its accessories withstood severe earthquakes with a magnitude of 6.90 and a maximum ground acceleration of 1.03 g with minimal damage. The recorded accelerations were used to determine the reduction in the quantity of shear modulus in the core and its improvement over time. A 50 million cubic meter landslide upstream of the reservoir is a reminder of the need to assess the potential impacts of large earthquakes on reservoirs.

5.2. Efficiency of dams in India Bhuj earthquake

On January 26, 2001, a magnitude 7.7 earthquake shook the western Indian state of Gujarat, killing more than 20,000 people and causing more than $ 3 million in financial losses. The nearest accelerator was located in Ahmadabad, 200 km from the epicenter. According to a report by Kriniterki and Heinz in 2002, the figure 8 shows a map of the area with Mercalli earthquake magnitude curves collected and presented. In this region of India, soft sand and silt (silt) have accumulated that extend to great depths. It is common to see in the figure that the saturation of these soils during an earthquake causes extensive damage, such as boiling sand, cracking of the ground, and embankments. According to Sitaram and Guindarajo in 2004, liquefaction was attributed to damage to many earth dams [36–38].

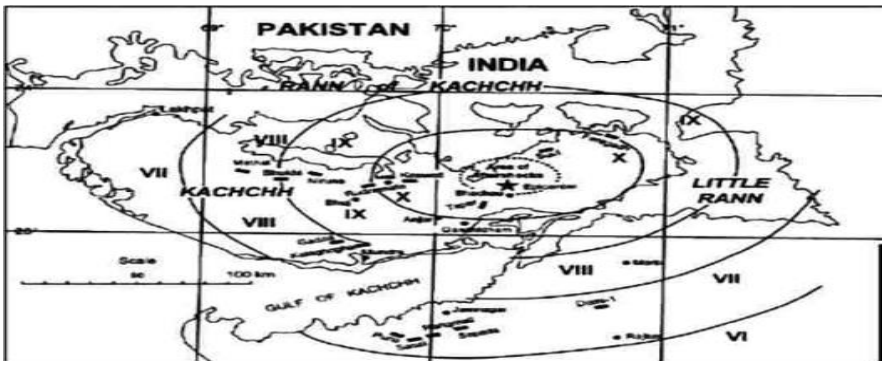

Fig. 8. Map of the Kachcheh area in India with earthquake intensity curves in terms of Mercalli [37].

5.2.1. Performance of earthen dams

Researchers such as [37–40]. Lateral thrust was examined. Many dams are built directly on soft sedimentary alluvial deposits, and researchers have attributed the liquefaction damage. There was little water in the reservoir after the earthquake, and the main damage to the dam occurred in the middle of the valley where the reservoir held saturated sediment. As previously mentioned, no information was available on the occurrence of severe movement near the dams. However, Grinterski and Heinz estimated the quake's magnitude in 2002 based on Mercalli visits to the area. In 2005, Singh and colleagues estimated the maximum acceleration using the distance to the epicenter and the specific damping relationship of the area. About 60 dams were repaired before the rainy season among the dams studied. In 2003, panels and superstructures examined the seismic capacity of dams because the next possible earthquake would be a cause for concern in the future, which is very important.

5.2.2. Selected historical items

Chang and Tapardo dams were among the dams damaged by the Bhuj earthquake. Observations at these dams showed that upstream liquefaction had led to deformation, lateral drift, and cracking. The two dams reacted very differently, and each of them will be examined in more detail in the next section.

5.2.2.1. Chang Dam

The dam was built in 1959 and zoned with a masonry wall, as shown in Figure 9. According to various reports, the dam's height was between 15.5 and 17 meters. The foundation material was soft sediment on the bed sandstone. According to a research group, the dam was located 3 km from the new geological changes. The rupture upstream of the dam was in the middle section, with the drop of the dam crown to an estimated 10 meters. However, the swelling was observed in both the upstream and downstream slopes of the heel. According to the panel and Brahmayat in 2003, several large longitudinal cracks were observed in the crown and upstream slope, as shown in Figure 10. The core and the wall were also broken due to the deformation of the dam. The reservoir was almost empty at the earthquake. Still, several studies have indicated boiling sand near the top of the ridge (Figure 11), which indicates that the sediments were saturated and liquefied during the earthquake. In 2002, Tu Vata and colleagues tested the Swedish wave near the upstream toe and reported 2.5 meters above the soft sand foundation. According to Patel &

Brahmayat, in 2003, the dam was severely damaged before the rainy season. So a full-height cut was made in the valley to allow the flood to pass safely.

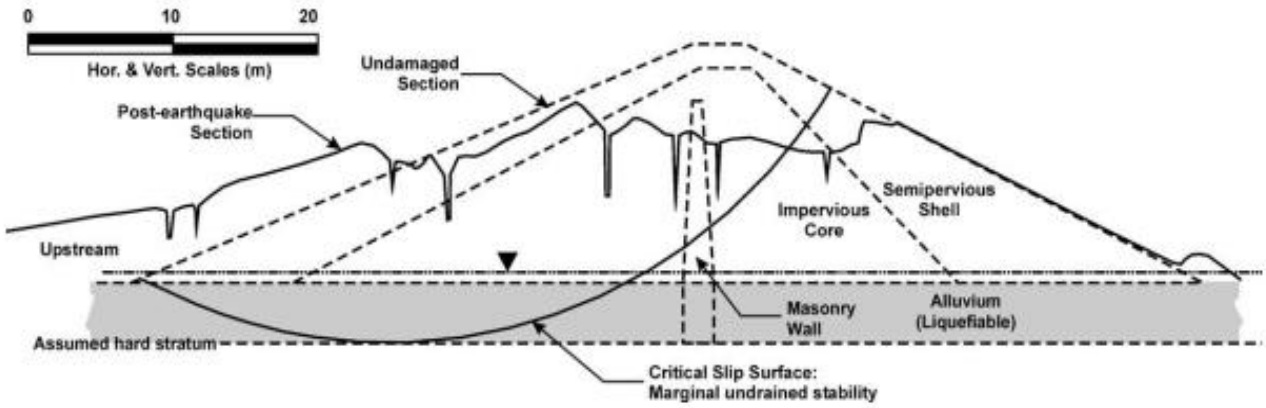

Fig. 9. Cross-section of Chang Dam, which shows the damaged and undamaged embankment. [39].

Fig. 10. A large longitudinal crack, approximately 10 meters, was found near the crown of Chang Dam [40].

Fig. 11. Sand boiling was observed in the Chang Dam reservoir near the dam claw [40].

5.2.2.2. Tapar Dam

Tapar dam was built in 1975 and is considered an important dam due to its agricultural and drinking water supply. During the earthquake, the water level inside the tank was very low but not dry. The topper has a height of 15.50 meters and is zoned in terms of materials, as shown in the figure 12. The design used the vibration coefficient, which led to the construction of booms

or slope breakers in the dam in the upper and lower claws. According to a 2003 report by Brahmariat and Judau, the dam was liquefied during the earthquake, which was covered with sand and detached near the upper claw, as shown in Figure 13. The landing at the crown was about 150 meters, and there were movements upwards [40].

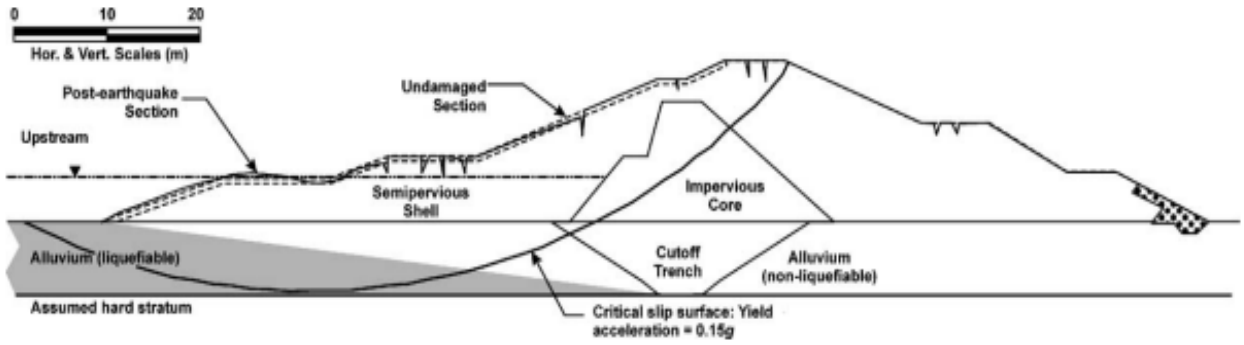

Fig. 12. The transverse section of Tapar Dam indicates the damaged embankment and has not been damaged [39].

Fig. 13. Lateral drift near the claw of the Tapar Dam [40].

According to Singh et al. According to Brahmayat & Judaw 2003, most dams were concentrated in the middle of the valley. The dam was virtually undamaged; there was no liquefaction near the piers. According to Krinitzki and Heinz in 2002, as shown in Figure 14, the overflow wall was built on an unarmed masonry structure and was undamaged. However, the upper part of the control tower broke, and the tower also appeared to be tilted, indicating that the foundation materials had lost their strength. However, the cracked parts were dug in the crown of the dam and repatriated with impermeable soil and repaired. A one-meter-thick layer was also pounded in brooms (slopes) on both slopes. All the details of the repairs mentioned by Brahmabat and Jadaw were reported in 2003. [40-45]. Figure 15 showes damage to the Tapar Dam [37].

Fig. 14. Longitudinal cracks along with the crown of the Tapar Dam to a depth of 3 m [37].

Fig. 15. Damage to the Tapar Dam [37].

5.3. Colbon Dam, Chile

The dam suffered only minor damage on February 27, 2010, earthquake in Chile. The maximum acceleration measured in the dam was 0.37 g.

5.3.1. Colbon Dam

It is an earthen dam with a height of 116 meters, 550 meters in length, and a volume of 130870,000 cubic meters, as shown in Figure 16. It has an oblique sandy core and a dense sandy crust. The river foundation is 68 meters deep. A concrete seal is made to control the leakage of the foundation. The 1,500 million cubic meter dam on the Maul River is located 30 km northeast of central Chile. Among the goals of this dam were irrigation water supply and electricity generation. The dam was completed in 1985. There are three small streams around the reservoir.

Fig. 16. Slope to the right and downstream of the Kalbon Dam in Chile [41].

5.3.2. Maul earthquake

At 3:34 am local time on February 27, 2010, a magnitude 8.8 earthquake shook central Chile, according to Al-Nashai et al. The epicenter was reported 8 kilometers off the coast of Chile. Mile fault stretches more than 80,000 square kilometers on the coast. The Maul area suffered a direct impact with a long vibration duration of at least 100 seconds and a maximum horizontal and vertical ground acceleration of more than 0.60 g. The quake killed at least 521 people and caused almost half the death toll from the tsunami. More than 800,000 people were directly affected by death, injury, and displacement. More than 300,000 buildings were damaged to varying degrees, including several cases of destruction [42].

5.3.3. Dam performance

In this section, Nogwara reports on 2010 on all information on earthquake performance. The dam was 183 km away from the epicenter and the fault fracture. The accelerometer in the rock tunnel recorded a maximum horizontal acceleration of 0.37 g. The maximum vertical acceleration was 50% higher than the maximum horizontal acceleration. An electrical channel was displaced near the downstream edge of the crown by a maximum of 2 meters horizontally and approximately one meter vertically, as shown in Figure 17. But the downhill slope did not show a change in shape for the earthquake. The dam suffered some minor subsidence and displacement but was no more than 10 cm. The transverse cracks were about one centimeter thick, along with the crown adjacent to both supports. After digging, the Turks disappeared at a depth of 3 meters. In Casagrand's piezometers, there were no changes in either support. Pneumatic pyrometers also did not operate inside the dam [22].

Fig. 17. Electric duct downstream at the Colbolbone Crown [22] .

The performance of the Colion Dam in the face of a large earthquake has been sufficient. Lateral cracks on the sides were common in embankment dams with steep slopes in the free depth range. The displacement of the electric channel seems to have been due to the high acceleration in the crown of the dam. Unfortunately, no measurement of acceleration is available.

5.4. Conanto Viejo Dam

The dam suffered only minor damage due to the February 27, 2010 earthquake. The maximum ground acceleration was 0.38 g at the dam claw. The magnitude of the earthquake was higher than predicted in the dam's design. The embankment dam with a height of 32 meters, a central clay core, a dense sandy crust, and a sandy transition zone with fine materials have been selected, shown in Figures 18 to 20. The dam is 728 meters long and has a volume of 3 million cubic meters. As shown in Figure 19, the overflow and outlet of the structure are located to the north of a hill on the right side of the dam. The dam was built in stages between 1973 and 2006. According to Flores et al. In 1982, as well as Nogwara in 2010, the Chimbarango Dam is located 25 km north of central Chile and has 237 cubic meters of water reserves with an area of 4,500 hectares for irrigation, flood control, and production. Electricity is designed and built [22,42].

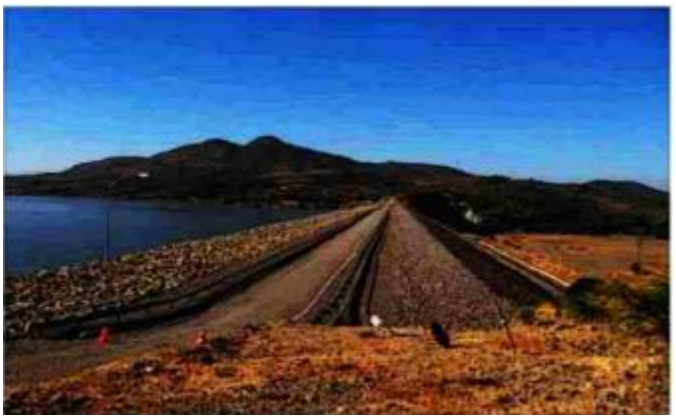

Fig. 18. View of the Conanto Viejo Dam from the right fulcrum [22] .

Fig. 19. Overflow downstream of the Conanto Vigo Dam [43].

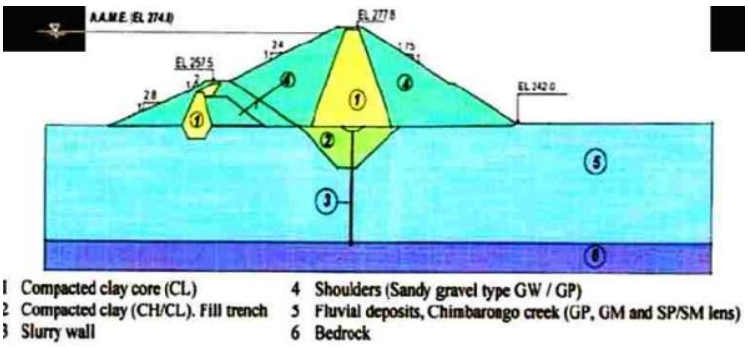

Fig. 20. Cross section of Conanto Vijo Dam [43].

The dam is made of river materials, mainly sand. The maximum depth of the foundation is 55 meters below the central part of the dam. Near the surface of the foundation in the central part of the dam was sand and silt with a maximum thickness of 10 meters with a high degree of density. Below this layer silty sands with relatively high density. This layer was 15 meters thick in the central part of the dam. Below this material and on the bedrock was a relatively high-density dune. 7 to 16 meters deep, the sealing trench was dug in the foundation and filled with dense clay. Due to the onset of winter and the consequent risk of flooding, an emergency operation was carried out by filling the right part of the trench under the sand with sand and most likely without density control. The depth of this filling was approximately 10 meters, and its length was about 180 meters, as shown in Figure 21[42,43].

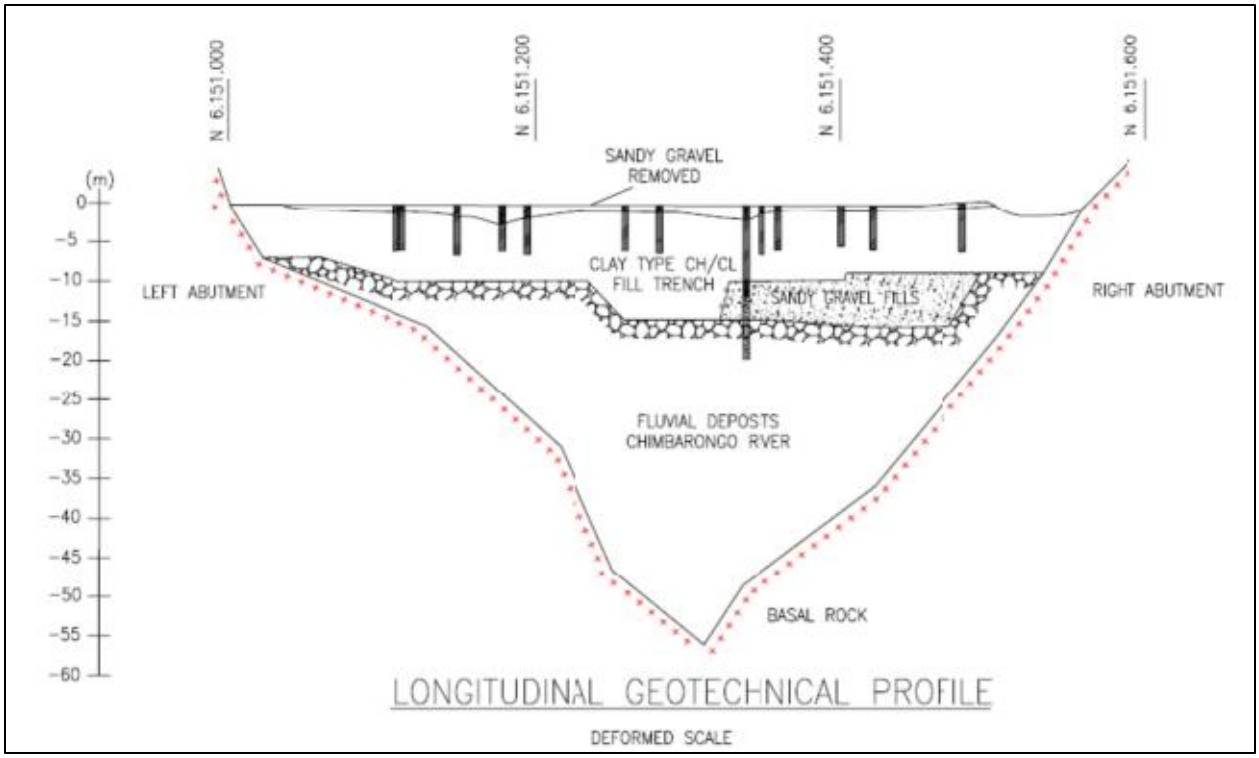

Fig. 21. Cross section of Kononto Vijo Dam Foundation [43].

A plastic concrete wall with a length of 500 meters and a sealing trench with a maximum depth of 55 meters, and river materials with 7.20 meters panels were built. At the design time, tensile deformation behavior and dynamic embankment responses were analyzed using the finite difference method. Two sections, one above the sealing trench and the other almost with fine fine-grained materials, were analyzed.

5.4.1. Maul earthquake

At 3:34 am local time on February 27, 2010, a magnitude 8.8 earthquake shook central Chile, with the epicenter about 8 miles off the coast of Chile, according to Al-Nashai et al. Mile fault that stretches more than 80,000 square kilometers on the coast. The Manoel area suffered a direct impact with a long vibration duration of at least 100 seconds and a maximum horizontal and vertical acceleration of more than 0.60 g. The quake killed at least 521 people, causing almost half of the deaths after a tsunami. More than 800,000 people were directly affected by the deaths, injuries, and dislocations. More than 300,000 buildings were damaged to varying degrees, including several cases of destruction [42].

5.4.2. Earthquake performance

The dam and the overflow outlet structure functioned well during and after the earthquake. There were no signs of major problems or equipment inefficiencies. Partial longitudinal cracks were observed in the crown at the highest point of Khakirir. The maximum sitting was 279 mm. Seismic analysis of this leak predicted 230 mm. A significant depression in the crown is shown in Figure 22, approximately where the sealing trench was located [22].

Fig. 22. Depression in the crown along the sealing trench of the Konontobujo Dam [22].

The dam was located 251 meters from the epicenter and 90 kilometers from the fault fracture. Three accelerometers also set records. According to Nogwara, in 2010, the acceleration map of Az was located on river soils and recorded large aftershocks. According to a 2011 report by Campana et al., The February 27 earthquake at the foot of the Free Zone Acceleration Dam weighed 0.49 grams (the result of the East-West and North-South forces). This is 11% higher than the maximum probable earthquake accepted in seismic hazard studies. There are 14 Casagrand accelerometers, 7 in the core, 7 in the foundation below the sealing trench and downstream of the limestone wall, and 15 electric piezometers downstream of the filter and downstream of the foundation. Water levels in all barometers increased during the earthquake; all but two returned to pre-earthquake levels three to three days later. The two were in the area where the sand was placed in the sealed trench. Electric sphygmomanometers also responded to the earthquake, but their readings in the earthquake decreased. According to Nogwara in 2010, barometer readings were also affected by several strong aftershocks [22,43].

5.5. Shin Yamamoto, Yamamoto and Asagawaral Dams, Japan

The construction of the Shin-Yamamoto, Yamamoto, and Asagawara storage dams and regulated water reservoirs for the Shinanogawa power plant has been supervised by the East Japan Railway Company, as shown in Figure 23. These three dams store the water of the Shinano River, one of the largest rivers in Japan. The Yamamoto and Shin-Yamamoto Dams are located in Lujia City, and the Asakawara Dam in Tokamachi City in the Niigata Basin. The power plants of these dams are used to supply power to Shingans superfast trains. A magnitude four earthquake occurred during the water transfer to the reservoirs for energy production, which quickly suspended the power plant and emptied the reservoir with an emergency evacuation. Due to the power outage of the power plant, the emergency drainage gates of the tanks could not be opened to drain water, so the remaining water flowed in the tunnels into the tanks to temporarily increase the water level inside the tanks and generators could generate electricity. Open the valves to empty the tanks. All three earthen dams and their power plants were damaged on October 23, 2004, by the Niigata Ken Chutsu Earthquake (also known as the Niigata Midlands Earthquake). The dams took about 18 months to complete and were completed in March 2006. In the following, the distance between the location of these three dams and the Niigata-Can earthquake center is examined [44–46].

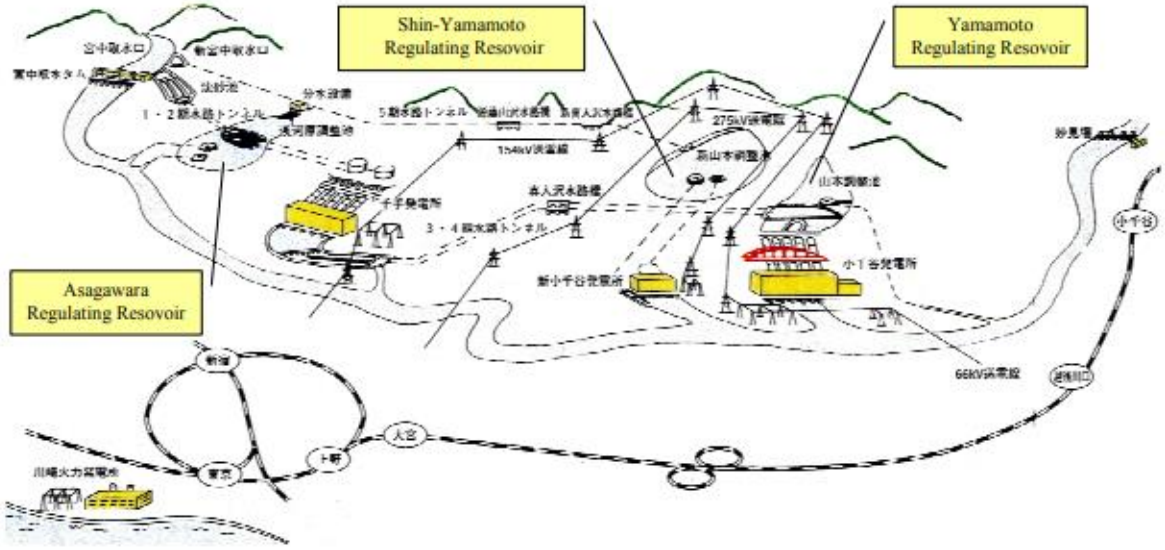

Fig. 23. Location of Shinogolva power plant reservoirs [16].

5.5.1. Shin Yamamoto Dam

The new Yamamoto Dam is located about 1/3 of a mile from the epicenter of the Niigata-Can earthquake. This dam is an earthen Dam zoned with a shell of mixed soil and upstream drainage. The filter and the central core are composed of clay, sand, and gravel. It is made of soft Pleistocene sedimentary rock. Shin Yamamoto Dam has been used to generate peaks that lead to rapid return flows daily, so an upstream drainage system has been designed for this relatively new and modern dam. The dam was built in 1990, and the axis of the dam is in the shape of a semicircle. The height of this dam is 139 feet, and its crown length is 4567 feet. The dam has various equipment such as sensors, including a piezometer and different gauges for measuring subsidence and six seismographs (accelerometer), 4 of which are located in the crown of the dam and two on the pavement of the downstream slope. [45] which is shown in figure 24.

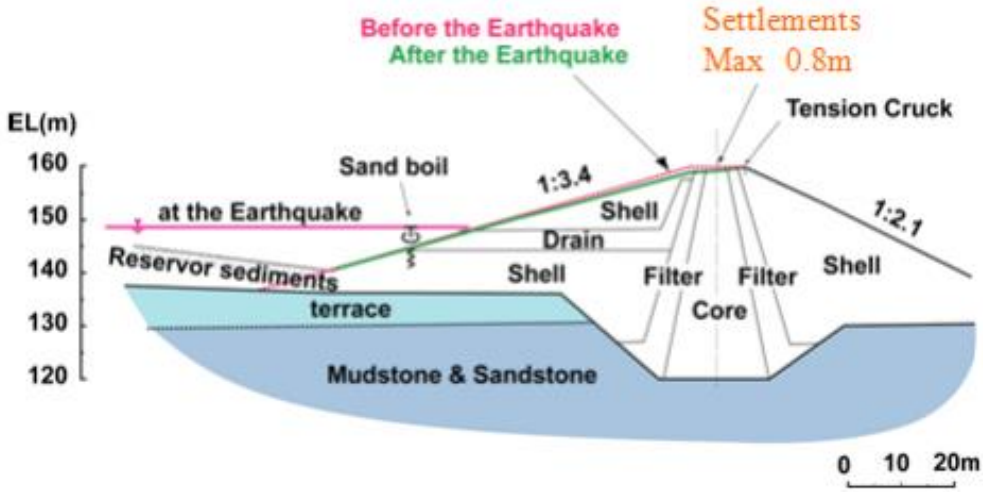

Fig. 24. Cross-section of Shin Yamamoto Dam [45].

5.5.2. Yamamoto Dam

The Yamamoto Dam is located approximately 3.70 miles from the epicenter of the Niigata-Can earthquake. This dam is a zoned earthen dam that was built in 1954. Its height is 92 feet, and its crown length is 3041 feet. The central core is composed of clay and sand compositions of the riverbed and the upstream and downstream crusts of sedimentary sand of the Shinano River bed. The concrete sealing wall with a minimum thickness of 2.60 feet is installed under a gap in the crown of the dam on the right support side with a length of 164 feet [46].

5.5.3. Asagawa Dam

The Asagawara Dam is located approximately 13.70 miles from the epicenter of the Niigata-Can earthquake. This dam is a homogeneous earth dam that was built in 1945. The height of this dam is 121 feet, and the length of its crown is 958 feet. The core and shell of the dam are made of 40% clay soil, while the downstream shell is made of coarser material with a maximum diameter of 100 mm. The concrete sealing wall is located along the main axis of the dam, Figure 25 [46].

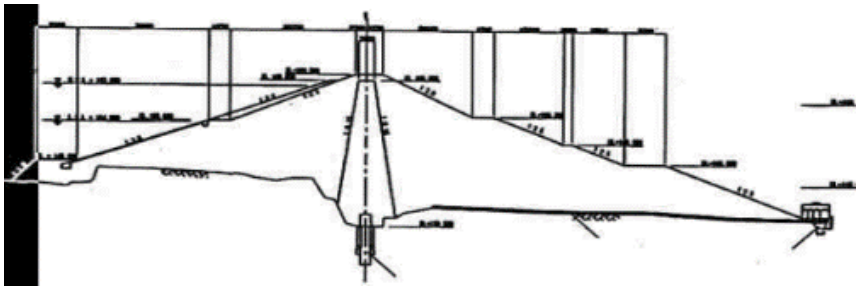

Fig. 25. Cross section of Asagawara Dam [46].

5.5.4. October 23, 2004, earthquake

On October 23, 2004, the Niigata-Ken Chongqing earthquake had 6.60 (known as the Niigata Middle Earthquake). Part of the aftershock was a strong earthquake that struck Honshu Island. " The epicenter was reported at 37.30 North and 138.80 East at 15.80 km. The epicenter was reported below the Pacific Ocean floor. However, no tsunami alert was issued. NW / SE, The maximum acceleration of this earthquake, was recorded in Ojai seismic station; the closest area to the epicenter of the earthquake was about 1.50. The earthquake caused significant damage to many buildings, roads, and railways. One person was killed, and 4,805 were injured [16].

5.5.5. Earthquake effects and observed performance

5.5.5.1. Shin Yamamoto Dam

Surveys performed on the dam body after aftershocks showed significant subsidence and parallel cracks along the dam axis, boiling sand, and shallow and shallow slip deformations. The studies also showed some soft soil in the upstream drainage, liquefaction in the upstream crust, and subsidence. The amount of soft soil in the upstream drain was higher than the amount considered during construction. Due to quality control and strict monitoring during construction, this amount should be combined with the original value during an earthquake. Exploratory excavations to study the boiling sand have shown that liquefaction was limited to shallow surface materials (up

to three meters above the surface). It is believed that the lower part of this layer was not compacted enough to prevent the sand from moving toward the surface during a severe earthquake. The maximum subsidence in the core clay thin layer near the dam at the left abutment was about 2.80 strength, which is 2% of the dam height. The meeting was distributed along with the central core [45].

5.5.5.2. Yamamoto Dam

Earthquake damage at the Yamamoto Dam included superficial slip deformations, boiling sand on the upstream slope, and transverse cracks along the right embankment at the dam crown. Dam body subsidence in all structures is measured at about 0.30 to 0.40 feet. Examination of the trenches after the aftershocks shows that the source of the boiling sand was up to a depth of 3.30 feet above the surface. Slip deformations are superficial and have a maximum of about 60.1 feet. During the earthquake, deformations due to sand liquefaction and surface slip were observed to be flush with the water level inside the reservoir [46].

5.5.5.3. Asagawara Dam

Damage to the Asagawara Dam has included cracks in the dam crown and stepping on the uphill slope. Along with the crown of the dam, several transverse gaps have occurred along the axis of the dam, and stepped subsidence with a maximum difference of 1.70 feet has occurred along the centerline. The maximum subsidence of the dam body was 2.50 feet, and no deformation caused by the earthquake was observed on the upstream and downstream slopes of the dam. According to post-earthquake surveys, the cracks and steps created after the aftershocks are deeper and upstream, with a maximum depth of 10.8 feet. The deformation of the dam crown was also developed due to the lack of proper density in the upper 3 meters of the dam body [46].

5.5.5.4. Instruments and accelerometer records

The maximum acceleration of the earthquake in the foundations of these three dams has not been accurately obtained. Still, the movements caused by the earthquake are at the type 2 level, and its maximum acceleration is estimated to be more than 0.5 g. The available data show that the highest accelerations are recorded during the reverse fault in the dam wall. Therefore, the movement of land at the dam site depends on the magnitude of the earthquake, the distance from the earthquake center, and the focal plane of the fault.

Damage to the three dams of Shin Yamamoto, Yamamoto, and Asagawara in the October 23, 2004 earthquake, with a magnitude of 6.80 in the Niigata-Ken Chutsu region, was almost minor. Although body subsidence and landslide deformations have occurred in all three dams, post-earthquake studies confirm that these dams' ability to store water has not been compromised. There has also been no leakage or leakage in these dams. Hydroelectric generators must be switched off immediately during an earthquake, although there will be no alternative energy or generator system for post-earthquake valve operation. Of course, this situation can worsen if some other unforeseen incidents occur at the same time and the trapped water cannot be released and evacuated. (Study History of the [45,46]).

6. Summary

In this review article, the behavior of earthen dams under earthquake movements is investigated. Earthen dams have a satisfactory performance when exposed to strong seismic motion. Typically, their performance is related to the nature of the soil used for the structure. Most well-constructed earthen dams are capable of significant earthquake vibration without harmful effects. Dams made of compacted clay materials on clay foundations or bedrock withstood strong ground movement.

1- In comparison, older embankments made on sandy materials or made of sand or silt with inefficient density and tailings dams all showed almost certain cases of failures that were originally due to the liquefaction capability of these materials. Dams are one of the types of hydraulic structures in this period, and tailings dams are the most dangerous types of earth dams.

2- Studies on these dams show that earthen dams built in recent years with sufficient equipment and following standards have improved significantly and can withstand severe earthquakes.

3- The more accurate and durable equipment and tools are used during the construction and operation of the dam; the less deformation is created in the dam and the more controllable it becomes.

4- Using up-to-date knowledge and benefiting from the experiences of construction and maintenance of the dam can help the optimal management of the dam during construction and operation.

5- Earth dams have better flexibility to accept dynamic load due to earthquake force than concrete dams.

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