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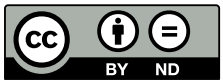

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Strengthening of Angat Rockfill Dam and Dykes due to Identified Dam Safety Deficiencies

Stefan Ehlers
Stephen Moll

The Angat mulitpurpose storage scheme is located on Luzon Island in the Philippines. Angat reservoir is impounded by a Main Dam, a Main Dyke and a Secondary Dyke, which are rockfill dams with inclined earthfill core. The Main Dam has a height of about 130 m. Comprehensive safety evaluations and analyses revealed that international state-of-the-art dam safety requirements are not met.

For strengthening of the embankment dams a stabilizing fill at the downstream slopes was designed and tendered. This paper informs about the current status of the construction works. In addition, the heightening of the core was initially foreseen at the Main Dam. By performing additional geotechnical investigations and updated stability analysis it was possible to demonstrate that the core heightening is not required.

Keywords: Dam safety assessment, dam strengthening, rehabilitation

1 Introduction

The Angat storage scheme is located in a highly seismic area on Luzon Island in the Philippines, around 60 km upstream of Metro Manila. The multipurpose project was built in the 1960s and provides potable water to Metro Manila and water for irrigation to farms, serves as flood control storage, and generates hydroelectric power. The Angat reservoir is formed by the Main Dam, Main Dyke and Secondary Dyke (Figure 1).

Main Dam, Main Dyke and Secondary Dyke are rockfill dams with inclined impervious core. The Main Dam has a height of about 130 m. The Main Dyke is located on the ridge of a hill and has a height of about 40 m in its center, whereas its downstream slope has about the same height as the Main Dam. The Secondary Dyke is adjacent to the Main Dyke and has a height of about 20 m. The downstream slopes are steep with an inclination of 1(v):1.4(h) at the Main Dam and 1(v):1.3(h) at the dykes, respectively. Upstream and downstream of the core three filter zones were designed, each with a width of 3 m.

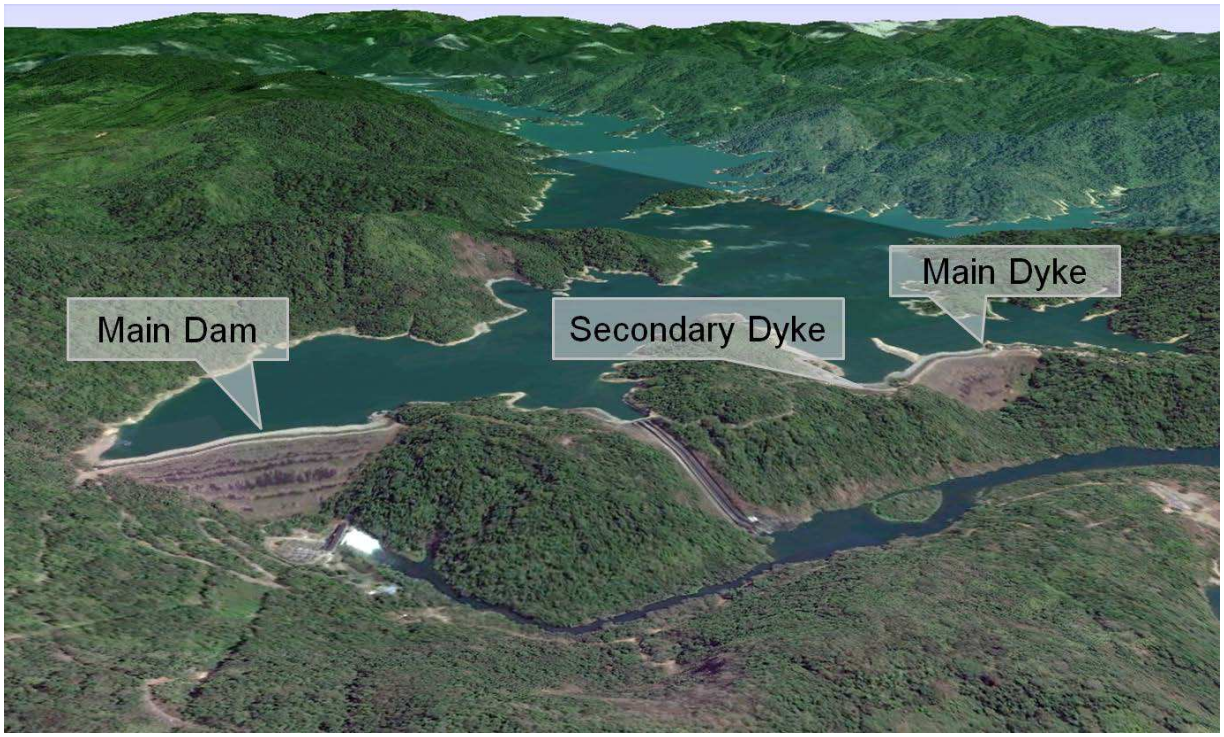

Figure 1: Angat reservoir formed by Main Dam, Main Dyke and Secondary Dyke; status before the strengthening works (*Google Earth, 2015*)

2 Safety Evaluations

2.1 Dam and dykes classification

In 2015, Pöyry has carried out safety evaluations of the Angat dam and dykes. The safety of the Angat scheme is of major importance because a dam or dyke break, in the worst case, would lead to flooding of large areas downstream including Metro Manila with its about 13 million habitants. Loss of life and considerable damages at infrastructure would be expected. Angat dam and dykes are classified as large dams with extreme consequence rating.

2.2 Flood Safety

The flood safety of the Angat multipurpose scheme was evaluated under consideration of the Probable Maximum Flood (PMF) and flood events with return periods of 10,000 and 1,000 years.

At the Angat scheme the PMF event is decisive for the evaluation of the flood safety. The PMF was determined on the basis of the Probable Maximum Precipitation (PMP). A comprehensive meteorological PMP assessment provides the state-of-the-art framework for the determination of most extreme precipita-

tion events as advocated by the World Meteorological Organization (*WMO, 1986; WMO, 2009*; Figure 2).

For transformation of the PMP into the PMF an event based hydrological model has been applied. The 48-hour event is crucial for the assessment of the flood safety. Its peak discharge is 13,680 m³/s and the total flow volume is 629 million m³.

Flood routing calculations were carried out considering the current Angat flood operation rules to obtain the reservoir levels. The freeboard safety check revealed that flood safety is provided, as long as it is ensured that all three spillway bays are operable and will be open during a serious flood event.

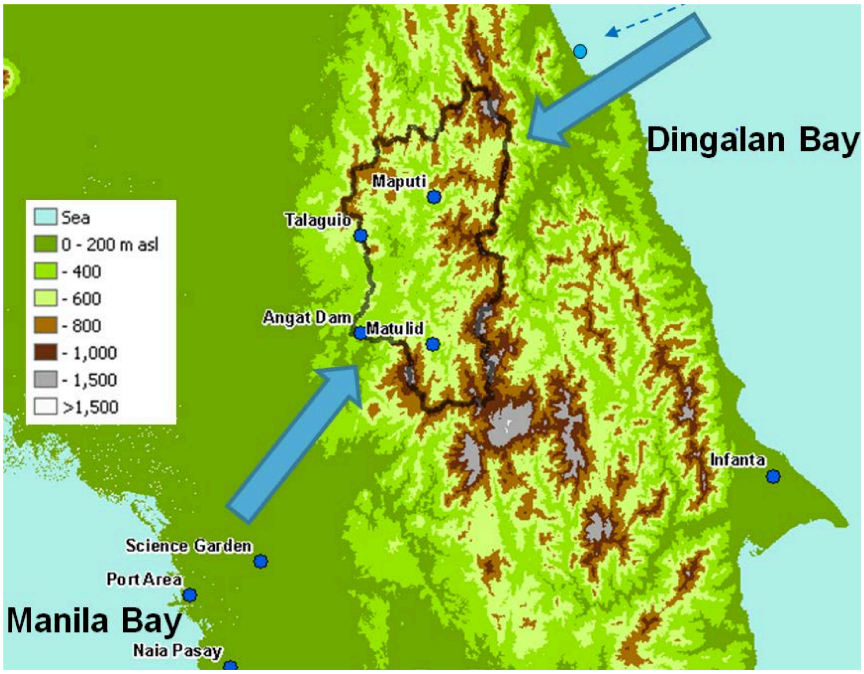

Figure 2: Angat catchment area and its surroundings with meteorological stations (blue dots); blue arrows show the most critical moisture inflow from Manila Bay and from Lamon (Dingalan) Bay

2.3 Stability analyses, static load cases

Stability analyses have been carried out at the highest sections of Main Dam and Main Dyke and by means of a Finite Element Model (*Geo-Slope, 2008*). Seepage analyses were performed in order to determine the phreatic line within the dam bodies considering the steady-state flow condition. The factors of safety calculated for the static load cases showed that the upstream slopes of the dam and dykes meet current safety criteria. However, the downstream slopes did not satisfy these criteria. The critical slip circle of the downstream slope of the Main Dyke with a safety factor of 1.38 is shown in Figure 3.

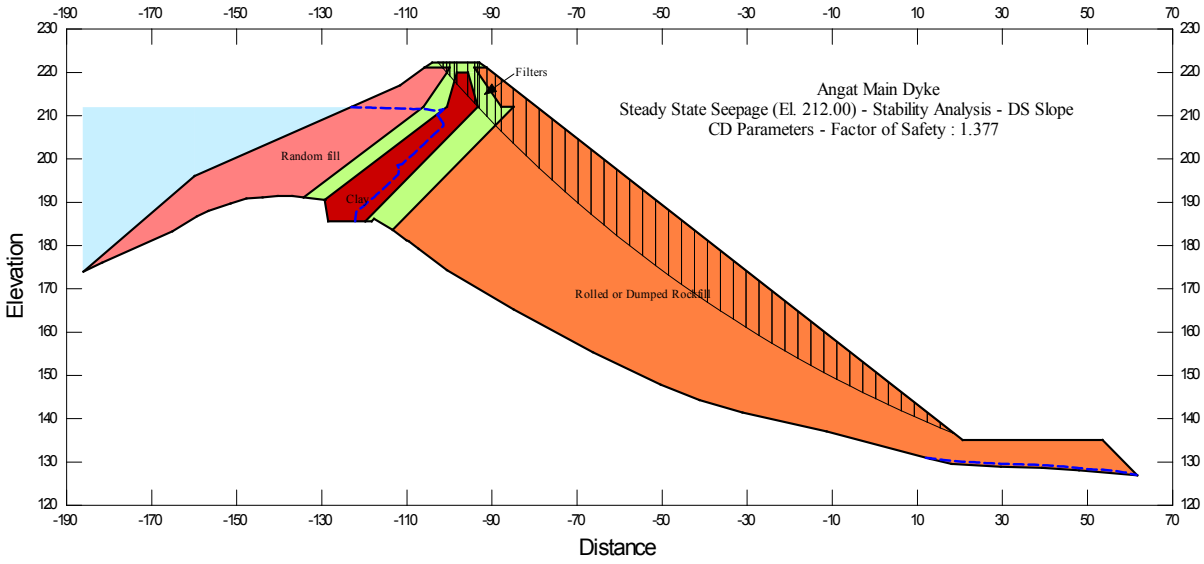

Figure 3: Stability analysis result of the downstream slope of Angat Main Dyke

2.4 Earthquake stability and deformation analyses

The Angat multipurpose scheme is located in a highly seismic area. Seismic stability analyses were carried out in accordance to the recommendations of the International Commission on Large Dams (*ICOLD, 2016*). The Safety Evaluation Earthquake (SEE) turned out to be the crucial, which is the maximum level of ground motion for which the dam should be designed or analysed. There must not be any uncontrolled release of water when the dam is subjected to the seismic load imposed by the SEE. Three different deterministically determined earthquake time histories were considered in the analyses. The horizontal peak ground acceleration (PGA_h) of the SEE at the dam sites on rock surface of up to 0.94 g (at the Main Dyke) has been determined (*Pöyry, 2015*).

Nonlinear dynamic response analyses were carried out using the equivalent-linear method (*Seed and Idriss, 1970*). The permanent earthquake-induced displacements were estimated according to the calculation procedure proposed by Newmark (*Newmark, 1965*). Potential sliding masses were selected and their yield accelerations were calculated by performing static slope stability calculations.

The permanent displacements were calculated by integrating the time history of the relative sliding velocity produced by the acceleration pulses exceeding the yield level. Significant slip circle sliding displacements of up to almost 9 m have been calculated at the embankment dam slopes.

Excess pore pressures produced in the core and the filter layers of dam and dykes during the earthquake reduce the effective stresses in these zones. How-

ever it was possible to demonstrate that the post-earthquake slope stability is provided.

2.5 Evaluation of the earthquake safety

The critical seismic failure modes of embankment dams are loss of freeboard (overtopping) and internal erosion:

(i) Loss of freeboard due to crest settlement

Sliding of the upstream and downstream slopes plus densification of the embankment material (*Bureau, 1997*) would lead to considerable crest settlement due to the SEE. The freeboard criteria were met for the Main Dyke and the Secondary Dyke but not for the Main Dam.

(ii) Internal erosion due to offset of the filter zones

The predicted slope movements would cause an offset of the filter zones. As the upstream and downstream filter zones might not remain functional after the SEE, seepage paths may develop along cracks and the critical slip surfaces leading to internal erosion.

2.6 Potential fault displacements

The West Valley Fault (WVF), a potentially active fault, takes course in a distance of only about 200 m to the left bank of the Main Dyke. During a strong earthquake deformations could occur at existing sub-vertical fault planes in the footprints of Angat dam and dykes. The maximum displacements were estimated to 5.3 m by means of an empirical formula reflecting the strike-slip nature of the WVF (*Wells et al., 1994*). Angat dam and dykes might not be able to cope with such large deformations due to the hazard of a concentrated leak developing suddenly along the rupture surface formed in the embankments.

There is considerable uncertainty in estimating the magnitude of potential fault displacements. Therefore a morphotectonic study is carried out to better characterize the neotectonic environment of the project. The investigations started in 2016, and are supported by the Philippine Institute of Volcanology and Seismology (PHIVOLCS).

3 Rehabilitation Concept proposed in 2015

The downstream slopes of Main Dam, Main Dyke and Secondary Dyke did not fulfil the required level of safety. Therefore it was proposed to place a stabilizing fill at the downstream slopes of Angat dam and dykes. The required average inclination of the stabilizing fill was determined to 1(v):1.6(h) (Figure 4).

For the Main Dam the loss of freeboard was predicted due to a strong seismic event (SEE). Therefore the heightening of the core by about 1 m was foreseen.

Due to the limited information available about the material properties of the embankment dams, it was recommended to verify the assumptions made for the structural analyses in more detail by means of geotechnical investigations.

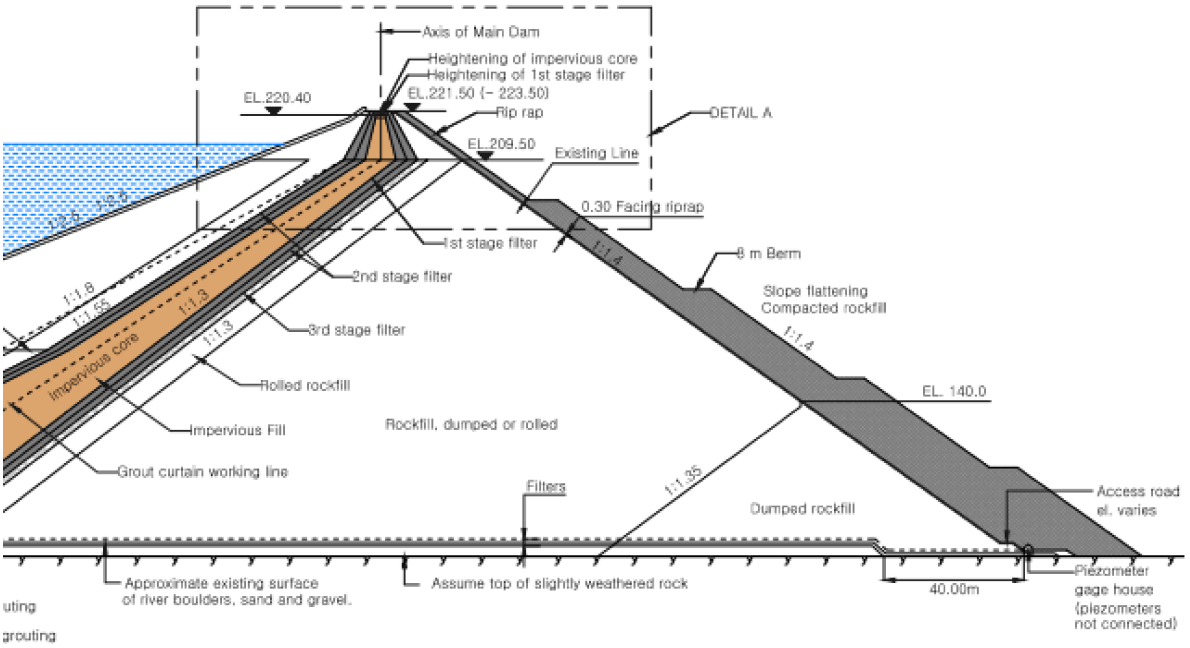

Figure 4: Strengthening of the Main Dam with a stabilizing fill at the downstream slope (grey area)

4 Geotechnical investigations and update of dam safety assessment

In 2017 a geotechnical investigation campaign was carried out to gain reliable information about the properties of the various layers of the embankment dams. The campaign comprised trenching at the crests, in-situ and laboratory testing. Beside geotechnical laboratory standard tests the focus was on the determination of the dynamic soil properties.

The resonant column test was carried out to determine the maximum dynamic shear modulus G_{max} and the strain dependency of the dynamic shear modulus and the damping ratio. Cyclic triaxial tests of core material provided important information regarding the pore pressure built-up due to cyclic loads.

The stability and deformation analyses have been updated considering modified and slightly more favourable geotechnical parameters (Table 1). Thus it was

possible to demonstrate that the freeboard criteria is also met for the Main Dam in the SEE load case. The contractor on site was informed in September 2017 that the heightening of the Main Dam's core is not required and shall not be carried out.

Main deformations caused by a serious earthquake would occur in the very upper part of Angat dam and dykes, where the water load and the hydraulic gradient are small in general. The properties of the core and the three stage filter are favourable with regard to their ability to cope with deformations. It was therefore concluded that the potential for internal erosion due to the SEE ground shaking is small. By spillway operation the reservoir level can be lowered relatively fast below the damaged dam zones.

Table 1: Estimated deformations at Angat Main Dam and Main Dyke due to SEE

	Sliding Movement		Vertical
	Upstream Slope	Downstream Slope	Settlement
Main Dam	4.7 m	2.0 m	4.6 m
Main Dyke	2.1 m	0.8 m	2.0 m

5 Implementation of the strengthening works

The strengthening works comprising mainly the stabilizing fill placement at the Main Dam, Main Dyke and Secondary Dyke were awarded as EPC contract. Preparatory works and quarry development commenced in October 2016 and placement of stabilizing fill at the Main Dam started in January 2017.

The quarry is developed at the right river bank downstream of the Main Dam on the ridge of a mountain, adjacent to an old quarry used during dam construction. The quarried rock is fresh to slightly weathered and durable volcanic and sedimentary rock, mainly Basalt / Diorite and Sandstone / Breccia.

Figure 5 shows an aerial photograph of the project site with the ongoing construction works.

The downstream faces and abutments of Main Dam and dykes are heavily overgrown, so thorough vegetation clearing is the first task to be done before placement of any new fill. Before placement of stabilizing fill against the existing dam surface, loose rock blocks are scraped off from the existing dam face to ensure a good bond and interlocking between old and new rockfill. Both the vegetation clearing and the scraping off of loose material is done simultaneously and advancing with the heightening of the stabilizing fill.

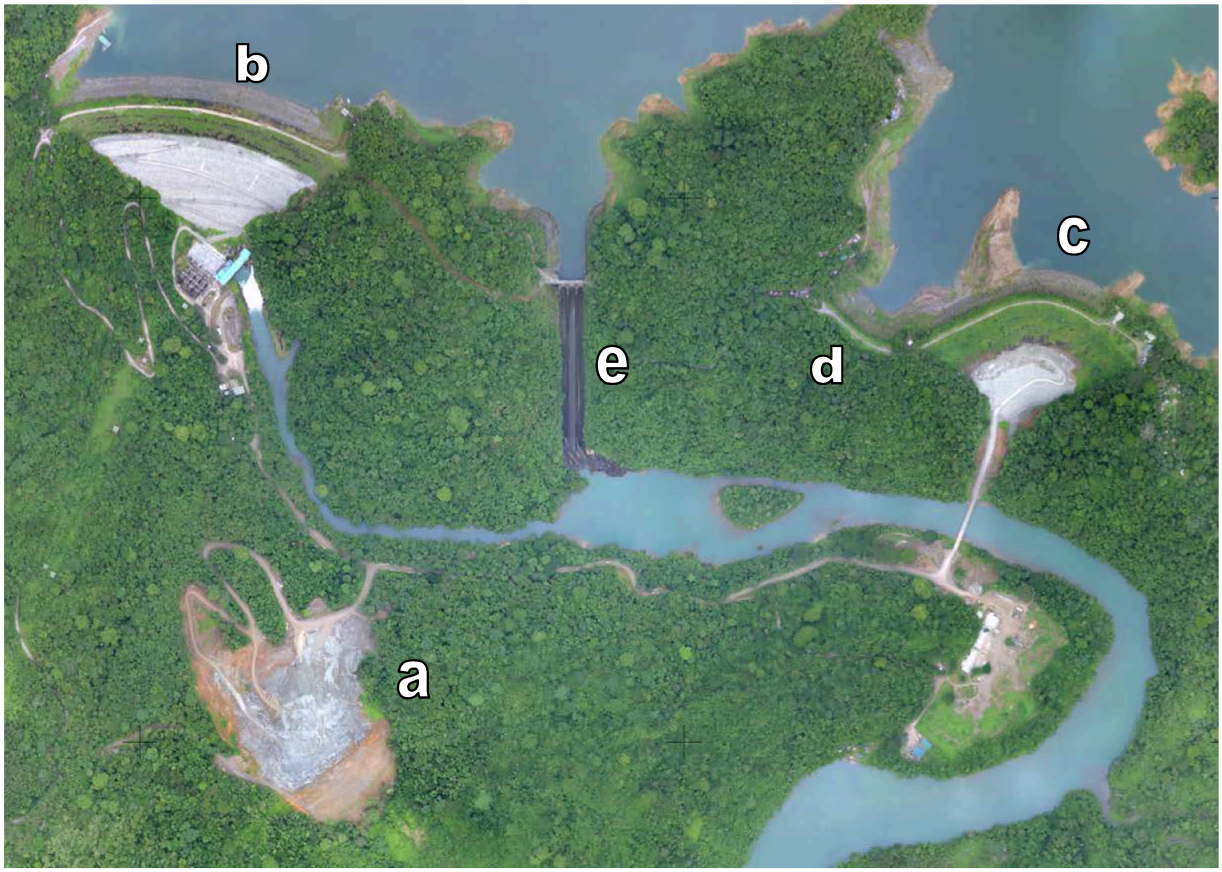

Figure 5: Overview of Angat site with quarry (a), Main Dam (b), Main Dyke (c), Secondary Dyke (d) and spillway (e)

The rockfill used for the stabilizing fill is well-graded with a maximum size of 800 mm and maximum 10 % of particles smaller than 4.75 mm. The stabilizing fill is placed in about 1000 mm thick layers and compacted by 8 passes of 12 t vibratory roller compactors. A photograph showing the placement of stabilizing fill material at the Main Dam is provided with Figure 6.

All rockfill material was placed without water sluicing because water sluicing is considered not to significantly increase construction settlement and because post-construction settlement of the stabilizing fill is not considered critical.

In locations were the abutments consist of highly to completely weathered rock or overburden soil a 3 m wide filter / transition layer of small gravelly rockfill is placed between abutment and stabilizing fill.

The total volume of stabilizing fill and rip-rap material required for the Main Dam and dykes is about 1.1 million m^3. Average monthly placement rates (total at Main Dam and Main Dyke) are about 70,000 m^3/month with a peak performance of about 105,000 m^3/month.

By the end of November 2017 the stabilizing fill placement at the Main Dam was completed up to EL 197.0 m asl and at the Main Dyke up to EL 175.0 m asl. Works at the Secondary Dyke will commence after the stabilizing fill placement at the Main Dyke is completed. This is to make use of the road on the downstream face of the Main Dyke as access road.

New monitoring instruments, which will be installed, include surface displacement points at the downstream dam and dykes faces, standpipe piezometers, seepage weirs at the toe of the Main Dam and Main Dyke and new strong motion recorder for earthquake monitoring.

The works are scheduled to be completed by mid-2018.

Figure 6: Placement of stabilizing fill at the Main Dam

6 Conclusion

Angat Main Dam, Main Dyke and Secondary Dyke are large dams classified as high hazard dams due to the large Angat reservoir volume and their location upstream of Metro Manila with currently about 13 million habitants. A comprehensive dam safety assessment was carried out to evaluate their compliance with international state-of-the-art dam safety requirements and their ability to safely withstand serious flood and earthquake events.

Required strengthening works comprising the flattening of the downstream slopes by placing a stabilizing fill were designed and are currently under construction. After the completion of the construction works Angat dam and dykes will provide a sufficient level of safety with regard to flood and earthquake safety in accordance to international guidelines.

A morphotectonic study is currently in progress to evaluate potential deformations along fault planes in the footprints of Angat dam and dykes due to strong earthquake events in more detail. The study is expected to be available in 2018 and based on the results the final dam safety evaluation will be concluded.

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