Dam modification designs for raising reservoir water level —case study of Tsengwen dam in Taiwan

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Abstract: The risk of failure of improving the existing dam safety during construction must be considered and weighed against the benefit obtained from the modification, and what can be done to minimize the risk during construction should be taken into account. In Tsengwen Dam Raise Reservoir Water Level Project at Taiwan, the greatest construction risk is the overtopping of the dam by flood when the crest is lowered by excavations. To secure the dam safety during construction, based on seepage analysis, required freeboard elevation check, stability and dynamic stress analysis of the dam, and flood routing, and considering the balance between optimum performance of the existing dam and economy and construction schedule, a compromise and integrated design should be needed instead of the mere construction of either a new upstream or a downstream filter zone.

Key words: filter design criteria; seepage analysis; dam safety

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水库大坝蓄水位提高工程设计——台湾曾文水库案例研究

摘 要：在对已建坝的加固过程中，必须考虑施工中的溃坝风险，权衡加固将产生的效益，考虑将风险降到最低程度的施工措施。在台湾省曾文坝水位抬高项目建设中，最大的施工风险是当坝顶因开挖而降低高程时洪水引起的漫顶。为了保证施工期的安全，根据渗流分析，超高复核，大坝动应力及稳定性分析，洪水演进分析等成果，权衡了大坝的性能、经济效益及加固工期等要素，提出了一个更为全面妥善的设计方案，而不是仅仅简单地在上下游铺设滤层。

关键词：反滤设计标准；渗流分析；大坝安全

0 Introduction

Located in southern Taiwan, Tsengwen dam is a central impervious core of zoned earthfill embankment dam with a maximum height of 133 m and gross storage of 700 million cubic meters and water surface area of 17.1 km^2. Storage, surface area and dam volume exceeds 9 million m^3 is the largest and second highest dam in Taiwan. The location and general layout of Tsengwen reservoir are shown in Fig. 1. Crest length of Tsengwen dam is 400 m. An upstream cofferdam 60 m in height above foundation was incorporated into main dam. The elevation of the crest of existing dam is 235.1~235.9 m Fig. 2 and Fig. 3 shown the embankment profile and sections and zone materials.

1 Philosophy of modification designs

Tsengwen dam was constructed on October 1973. To meet the increasing water demand of southern Taiwan, reservoir storage 90 million m^3 is to be increasing by raising the normal water level from the existing El. 225.0 to El. 230.0 m. The general philosophy of modification for raising water level is to design the dam as much as possible to follow the current state of the art. The designers of the embankment, however, must find a best approach point between optimum performance of the

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existing embankment, and economy and construction schedule.

The original embankment filter criteria was designed by older methods, but the embankment has performed well to date. The existing filter zone was only constructed up to elevation 215.0 m in the downstream and 225.0 m in the upstream dam body as shown in Fig. 4. The unfiltered elevations between the top of Zone 3B and the top of the core would not be accepted under current design practice. To connect the new filter to the existing filter, the embankment must be excavated and treated down to elevation 215.0 m. This would cause higher risk of catastrophic failure of the

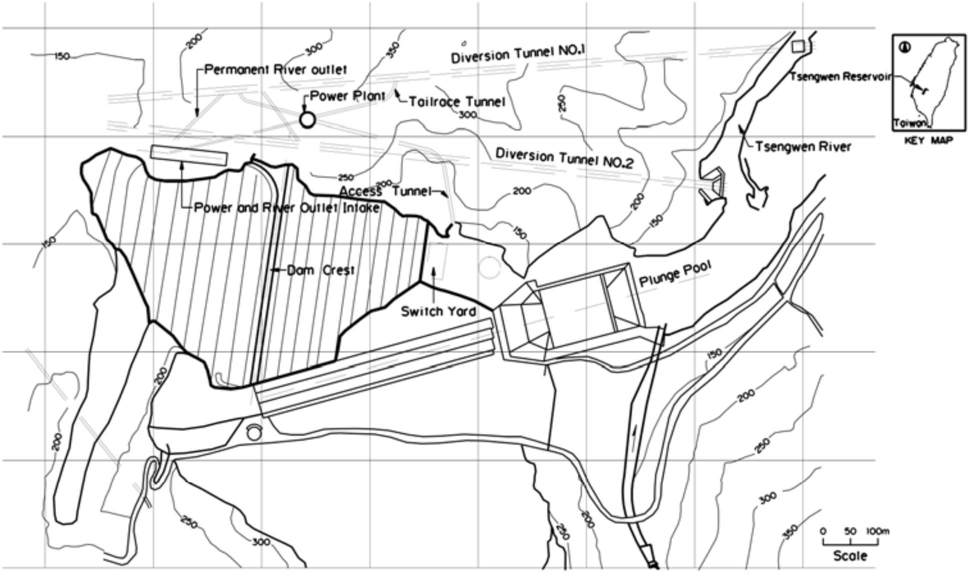


Fig. 1 Location and general layout of Tsengwen reservoir

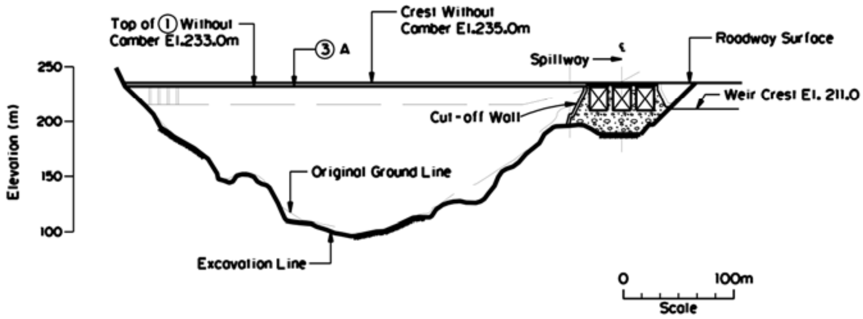


Fig. 2 Profile of Tsengwen embankment (along dam axis)

ZONE	DESCRIPTIONS
1	Mixture of Clay, Silt & Gravel (imperious Core)
2A	Selected Fine Weatheres Formation Materials
2B	Unweatheres Formation Materials
3A	Sand Gravel and Cobbles
3B	Sand Gravel and Cobbles Meet Filter Requirements
3C	Sand Gravel and Cobbles
3D	Pit-Run Sand , Gravel , Cobbles and Boulders
4	Boulders
5	Selected Unprocessed Materials From Required Excavation

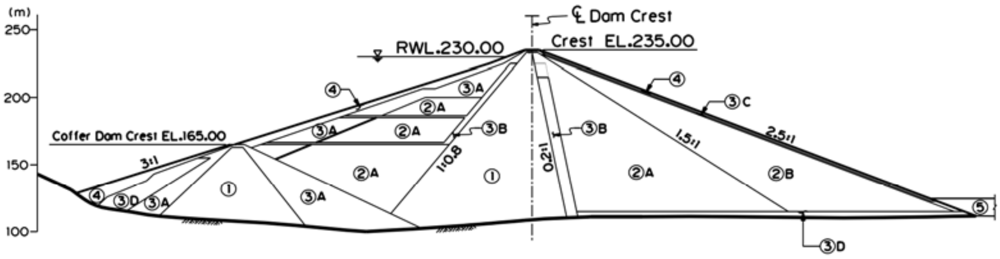


Fig. 3 Cross section and zoned materials of Tsengwen embankment

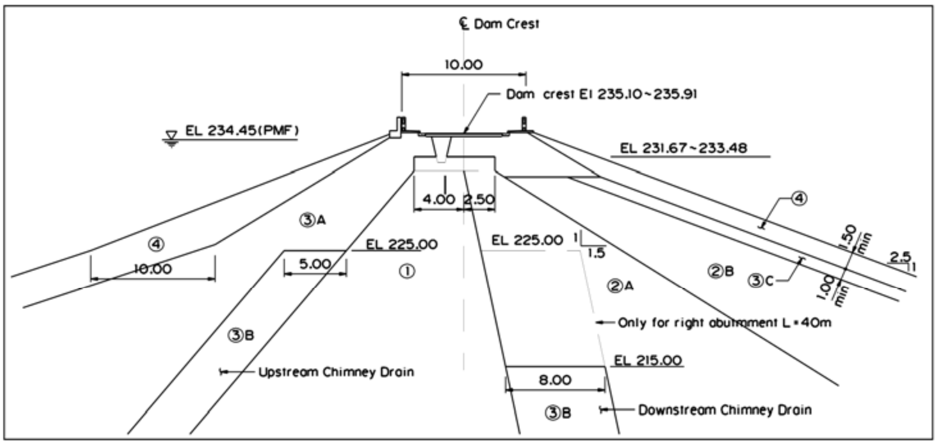


Fig. 4 Details of Tsengwen embankment dam crest

Table 1 Freeboards elevation of different normal RWL

Normal RWLH_n/m	Wave runupH_w/m	Wave EQH_E/m	AllowanceH_A/m	Max. flood water level (PMF)/m	Required freeboard elevation/m		Core top elevation/m	Dam crest elevation/m
					(1)	(2)		
225.0	0.79	0.99	1.5	234.13	228.28	236.42	231.67~233.48	236.30~237.0 (including parapet)
230.0	0.79	1.02	1.5	234.45	233.31	236.74		

dam by flood overtopping, because of the longer duration and the greater reduction in the crest elevation during construction. So, these two issues as following are what must be considered.

(1) Is it necessary to use new filter design criteria for the modification of existing embankment dam?

(2) Central impervious core of zoning rolled fill embankment dam with chimney drain, whether the height of upstream/downstream filters is necessary to design the same level as the height of central core or not ?

Tsengwen dam is located in a high seismicity area with PGA 0.67g during MCE (maximum credible earthquake = 7.4). In the past, well-constructed embankment dams have performed well even in severe earthquakes. What shall be considered while dam body has possible transverse cracks and extends to depths approximately 4~6 m in the abutment if MCE happened?

2 Considerations and analysis

2.1 Required freeboard elevation

The method for freeboard elevation computation is based on the Water Conservation Structure Inspection and The Safety Evaluation Technical Standards of WRA in Taiwan.

$$H_n + H_w + H_E + H_A \quad (H_W+H_E \geq 1.5\ \text{m}), \quad (1)$$

Where H_n is normal water level, H_w is wave height including run-up on riprapped slope, and $H_w \geq 0.5$ m, H_E is wave height of seismic action, and H_A is required allowance depending on type of dam and gated spillway.

$$H_F + H_w + H_A\ , \quad (2)$$

Where H_F is Maximum flood water level.

The total additional height H_A was 1.5 m, including gate controlling type 0.5 m and dam type 1.0 m.

All the different freeboards elevation in meter of different normal reservoir water level is shown in Table 1.

By comparing the top elevation of parapet wall and required freeboard elevation, the height of existing parapet wall is still 44 cm lower than calculated freeboard elevation 236.74 m in the normal water level would be raised to 230.0 m. Furthermore, the required core top elevation of dam after modification shall not less than PMF (EL. 234.45 m) in accordance with design criteria of U.S. Army Corps of Engineers.

2.2 Filter design criteria

For filter design, three necessities are termed, respectively, piping or stability requirement, permeability requirement, and discharge capacity. The Tsengwen embankment filter was designed by older methods and satisfied to the following requirements[1]: ① D_{15F}(filter) > $5D_{15B}$(core) for Permeability; ② D_{15F}(filter) < $5D_{85B}$(core) for Piping; ③ Minimum of 5% < #200.

The range of gradation of zone 1 and zone 3B and zone 3A material (maximum size 30 cm) are shown in Fig.5.

Table 2 Current design standards of filter adopted by US. Bureau of Reclamation

Base soil category	Base soil percentage finer than #200/%	Base soil description	Filter criteria
1	>85	fine silts and clay	$D_{15F} / D_{85B} \leqslant 9$
2	40~85	sands, silts, clays, and silty and clayey sands	$D_{15F} \leqslant 0.7$ mm
3	15~39	silty and clayey sands and gravels	$D_{15F} \leqslant 0.7$ mm,[(40−A)(4× D_{85B})−0.7 mm] / 25
4	<15	sands and gravels	$D_{15F} / D_{85B} \leqslant 4$

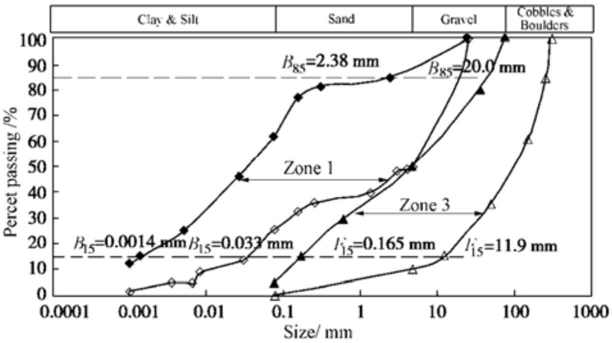


Fig. 5 Original gradation of zone 1 and zone 3B (filter)

The forms (typically $D_{15F} < 4$ to $5D_{85B}$) of older methods represent a "no-continuing-erosion" boundary, which means that some particles may be eroded out of the core, but erosion would soon cease and failure of the dam by piping would not occur[2]. If enough particles are moved into the filter, its permeability can be reduced significantly.

But current design standards, for the types of soils to be protected (Zone 1 primarily), the filter should have a maximum D_{15} value of 0.7 mm shown in Table 2. This is a "no-erosion" boundary, designed to prevent from any erosion of particles of core material out of the core into the filter zone[2].

Therefore, the filter shall be located 0.1~0.7 mm ($D_{15F} \leqslant$ 0.7mm for piping requirement, and $D_{15F} \geqslant 5 \times D_{15B} \geqslant 0.1$ mm for permeability requirement), but the existing filter material its D_{15F} was located between 0.165~11.9 mm, which to be obviously large.

However, the material of zone 1 and zone 2A, which is from almost the same borrow area its D_{15} was 0.022 mm smaller than far 0.7 mm. The fine grain material of zone 1 should be protected by the zone 2A even if seepage water through chimney drain. Furthermore, pore water pressure of core and filter are much lower, unclear seepage water from toe drain have not be monitor up to date. Although the filter material did not conform to current design standard, but still prevent from any erosion of particles of core material out of the core into the filter. Should it be very difficult to process a filter met the current criterion above, a less-stringent original filter design criteria for existing dam based on the older no-continuing-erosion approach is acceptable.

2.3 Seepage analysis

The filter drains of Tsengwen embankment consist of a nearly vertical filter drain (chimney drain) at El. 225 m for upstream, and at El. 215 m for downstream in top, and two blanket drains only upstream filter (one at El. 185 m, the other at El. 165 m, both crossing zone 2A).

The functions of the upstream filter are to ensure upstream slope stable during sudden drawdown, to prevent excessive loss of fine-grained core material due to flow out of the core during lowering the water level of the reservoir. Based on gradation of Zone 3A upstream of the core should be used as drainage and filter material not causing loss of core material, and upstream slope is stable and met to criteria according to result of stability analysis during reservoir water level El. 230 m sudden drawdown to El. 154m. Height of upstream filter are not need to be raised from El. 225.0 to El. 230.0 m have recommended.

In general and in current design standards, the downstream filter should be as high as (or nearly as high as) the core. But at Tsengwen dam, the existing downstream filter was only constructed up to elevation 215.0 m. If connect the new filter to the existing filter top, the embankment must be excavated and treated down to elevation 215.0 m. This would be the technically best approach, but cause higher risk of catastrophic failure of the dam by flood overtopping during construction. Therefore, seepage analysis including Casagrande formula, flow net by hand-drawing, 2D and 3D finite elements method to be performed to figure out and check the location of seepage phreatic line

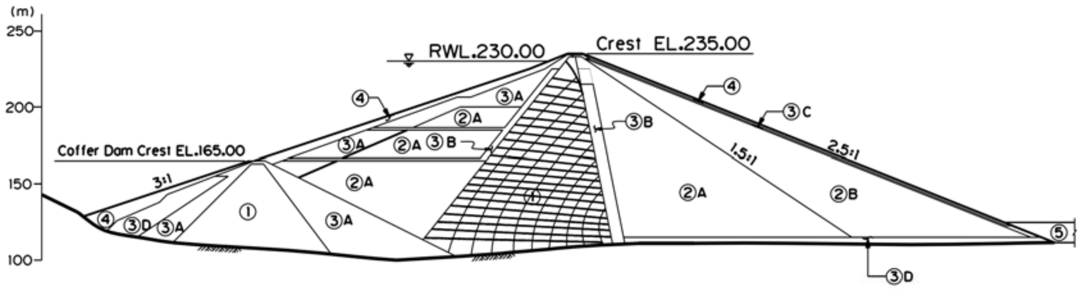


Fig. 6 Seepage analysis of flow net by hand-drawing

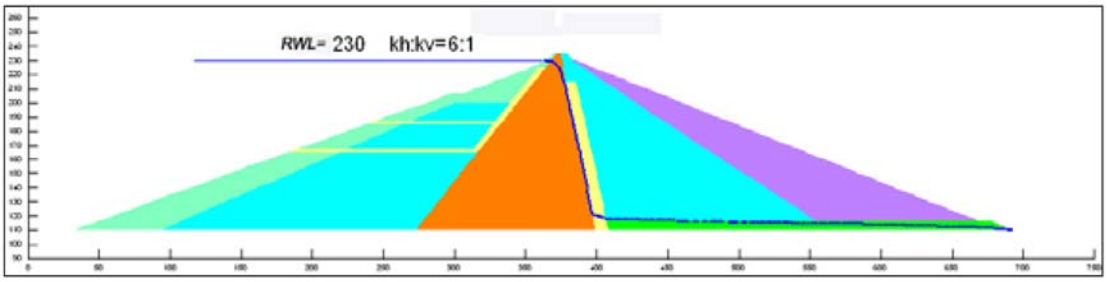


Fig. 7 Seepage analysis of 2D finite elements method

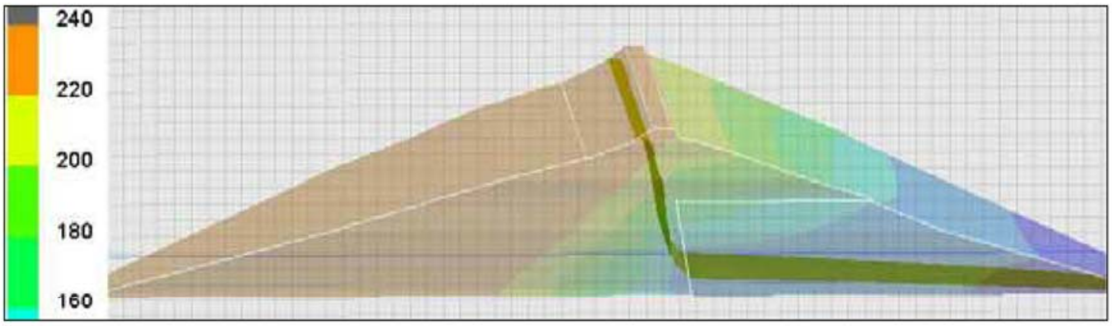


Fig. 8 Seepage analysis of 3D finite elements method

Table 3 Summary of seepage analysis results

Reservoir water level, El/m	Seepage exit at chimney drain or slope face, El/m (seepage quantity/(cm • m^{-1}))			
	Casagrande formula	Hand-drawing	2D FEM	3D FEM
225	183.3(2.4×10^{-6})	206(5.57×10^{-6})	120.5(5.0×10^{-6})	124(6.6×10^{-6})
230	187.9(2.5×10^{-6})	208(6.45×10^{-6})	121.0(5.8×10^{-6})	127(7.1×10^{-6})

without filters between elevations 215.0 m and 231.5 m. The results of seepage analysis are shown in Fig. 6 ~ Fig. 8 and summarized to Table 3.

Based on seepage analysis result, flow nets by hand-drawing have more conservative seepage exit than other methods, 3D FEM have more seepage quantity. Some important seepage behaviors for raising reservoir water level from 225 to 230 m are as following.

(1) The phreatic line close to downstream chimney drain and dropped down rapidly, and keep water flow in filter.

(2) Seepage quantity increases approximately 15% and phreatic line exit at downstream chimney drain slightly higher 0.5 meter by 2D FEM and lower than capacity of blanket drain.

(3) Maximum hydraulic gradient increases approximately 0~8%, and has not increased obviously.

By the way, downstream drainages perform well, pore water pressure of core and filter are lower than analysis in accordance with existing monitoring data. Therefore, the dam body has not the disadvantageous tendency of piping. Phreatic line under the top of downstream filters depends on different seepage analysis method, phreatic line adjacent to chimney drain dropped-down rapidly, and keep water flow in filters, downstream dam body no piping problem, so downstream filter not need to be raised from El. 215.0 to El. 230.0 m.

2.4 Slope stability analysis and dynamic stress analysis of embankment

Table 4 Summary results of slope stability analysis

Sliding zone extending thru.	MCE			Without EQ.	
	U/S slope	D/S slope	D/S slope (filter malfunction)	U/S slope (Rapid drawdown)	D/S slope (filter malfunction)
Top 1/4	0.9	1.1	1.1	2.4	3.1
Top 1/2	0.9	1.1	1.1	1.8	2.6
Top 3/4	1.0	1.2	1.1	1.6	2.2
Full dam high	1.1	1.4	1.1	1.6	1.9
safety factor required	1.0	1.0	1.0	1.2	1.5

The slope stability analysis is including static and pseudo-static approach method to analyze the static and seismic stability of embankment. Summary results of slope stability analysis are shown in Table 4.

The results of pseudo-static analysis indicated that all of potential slides will induce "acceptable" deformation under MCE except potential sliding through top 1/4 and top 1/2 of upstream slope. However, for accurate prediction on the performance of dam during earthquake, full dynamic analysis is essential.

The dynamic analysis used for Tsengwen embankment is based on the procedures developed in 1970's and provides a useful basis to evaluate the response of earth dams during earthquakes (Seed, et al., 1973). The general procedure of this method may be divided into three parts:

(1) Determination of static stresses in the embankment dam prior to the earthquake (Static Analysis).

(2) Determination of the embankment's response to the earthquakes, which includes the computation of induced shear stress-time histories for various locations in the embankment (Dynamic Response Analysis).

(3) Response evaluation of embankment to resist seismic events, which include liquefaction potential, deformations after earthquake and displacement of potential slides (Post-earthquake Analysis).

Results of dynamic analysis summarized as follows:

(1) Dynamic response analysis shows that the maximum acceleration on the upstream of the embankment are recognized as 1.4~1.6g under MCE. On the crest, the maximum acceleration is about 1.2~1.3g with amplification factor of 1.8~1.9.

(2) Under MCE time histories with M = 7.4 and PGA = 0.67g shown in Fig. 9, the average settlement on the crest is about 147 cm, i.e., 1.11 % of dam height shown in Fig. 10.

(3) The sliding block analysis shows that the sliding through the top 1/4 of embankment height exhibits the maximum displacement 96 cm.

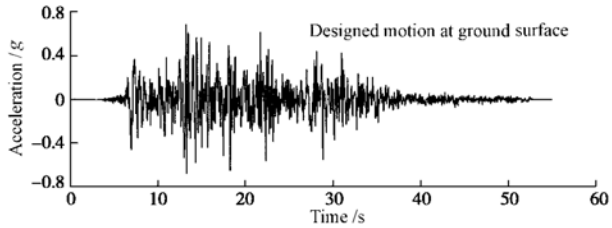


Fig. 9 Time histories of design earthquake MCE

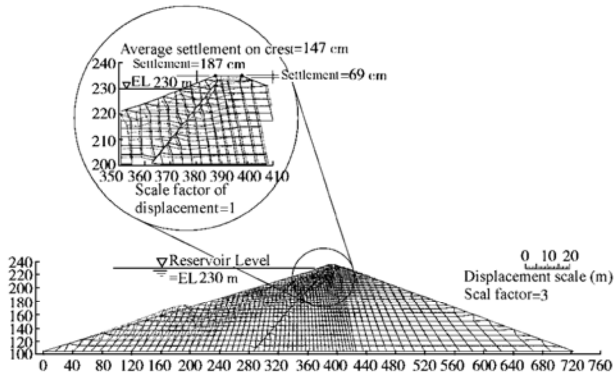


Fig. 10 Settlement of dam crest from dynamic analysis

(4) Only parts of upstream shell and upper potion of core with safety factor of liquefaction less than 1.0. Due to well-compacted dam, it will keep some tolerable deformation, but will not cause the failure mode of flow under design earthquakes.

2.5 Prevention from the cracks caused by maximum credible earthquake

From the result of dynamic analysis and Fong & Bennett 1995[3] as shown in Fig. 11, high potential of transverse crack may extend to 4~6 m near the abutment and lead to insufficient freeboard at N.W.L. of EL. 230 m under MCE and PMF combined effects.

Two protection measures have proposed to avoid piping caused by seepage water through cracks at abutment, although the above mentioned has the probability to be extremely low, which occurs the return period is 30000000 years, to be take the PMF as 10000 years, and MCE is three millennium years[1].

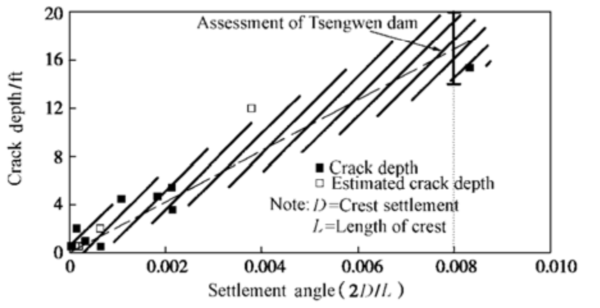


Fig. 11 Potential of transverse crack depth near abutment

(1) At first preventing and controlling measures.

a) Top of core zone is higher than the PMF water level.

b) Core zone to be widen (min. 5 meters).

c) Plasticity of the core material required to PI > 15, and the construction water content 1~2% more than OMC.

(2)Secondly protecting measures to incorporate a downstream chimney drain in the new core up to El. 235 m and connect to zone 3C to releasing seepage water if earthquake cracks happened.

3 Modification layout

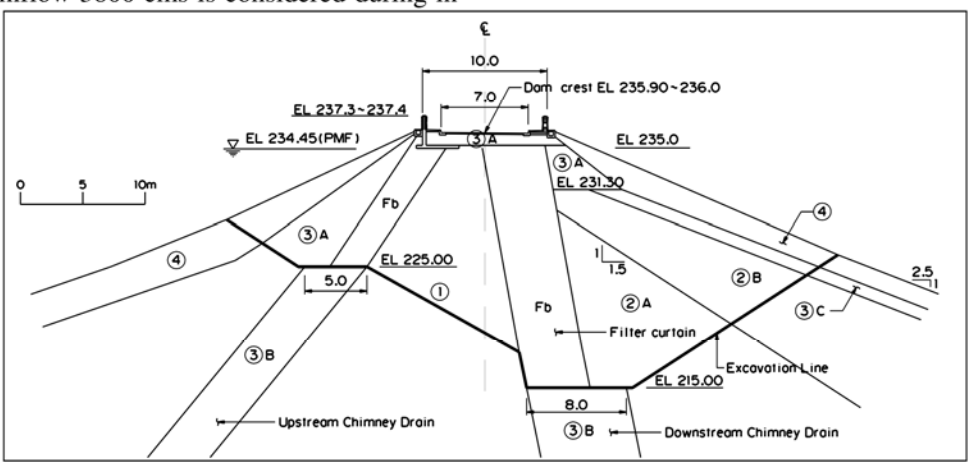
The risk of failure during construction of a particular design to improve the safety of the dam must be weighed against the benefit obtained from the modification, and what can be done to minimize the risk during construction. At Tsengwen dam, the greatest risk during construction is from overtopping of the dam by a flood when the crest is lowered by excavation. After flood routing, the risk probability correspond to different reservoir water level elevation shown in Table 5 in flood season (from June to October), 0.1% probability of overtopping from flood in 1 year if 1000 years return occurrence and inflow 3800 cms is considered during in dry season (from November to the May next year). The proposed construction and modifying of embankments to be study in accordance with above analysis of seepage and flood risk.

Table 5 Probability correspond to different reservoir water level in flood season

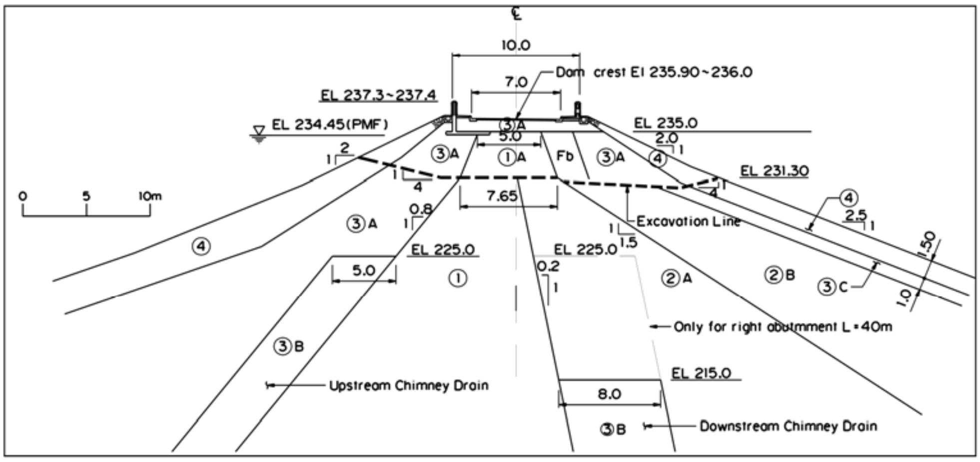
Max. inflow /cm	Max. water level /m	Max. outflow /cm	Return period /a	Probability /%
3080	222	2758	3	33.33% in 1 year
7200	227	5821	35	2.86% in 1 year

Three possible proposals for modifying the embankments have been studied as shown in Fig. 12.

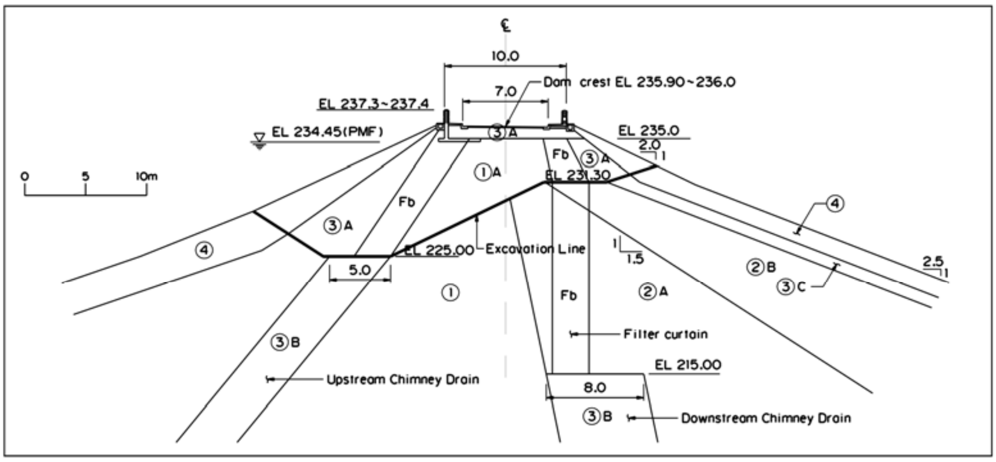
Plan 1 includes excavating a portion of the crest on the upstream side to elevation 225.0 m and excavating deep to 215.0 m on the downstream. The excavation was to allow upstream and downstream filter to be constructed down to connect the existing filter. Plan 3 includes the downstream filter curtain to be constructed down to elevation 215.0 m by drilling overlapping holes backfilled with filter sand, but not a new upstream filer. The excavated embankment would then be replaced with modern embankment zones including impervious core and foundation of parapet wall built into the central impervious core. Plan 1 would cause higher risk of catastrophic failure of the dam by flood overtopping during construction than the others would, because of the longer duration and the greater reduction in the crest elevation during construction. Downstream filter curtain in plan 3 may not have the same stiffness and strength characteristics as existing compacted embankment fill. How the filter would affect the response of the embankment during an earthquake is unknown.



(a) Plan 1



(b) Plan 2



(c) Plan 3

Fig. 12 Three possible proposed for modifying Tsengwen embankment

To secure the dam safety and keep enough water supply avoid from 0.23 billion m^3 water storage loss during construction, and from Section 3, it is recommended that plan 2 the crest can only be allowed to be excavated down to El. 231.3 m during dry season shown in Fig.12, instead of constructing either a new upstream or a downstream filter zone.

4 Conclusions

The unfiltered elevations between the top of existing Zone 3B and the top of the core would not be accepted under current design practice. Constructing a new downstream filter all the way down to Zone 3B is preferable so that there is no area of Zone 1 where the seepage is left unfiltered. The best solution technically would be to excavate to elevation 215.0 m so the whole filter coverage can be provided.

But after constructing a new filter down to Zone 3B fast enough to avoid from floods would be difficult and cause higher risk of catastrophic failure of the dam by flood overtopping during construction, then a compromise and integrated design should be used. All designs and construction operations must be performed to provide a safe structure during all expected conditions for modification of an existing dam.

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