SAFETY EVALUATION OF BAKUN CONCRETE FACED ROCKFILL DAM

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BY

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ABSTRACT

This study deals with a 2-D plane strain finite element analysis of elastic linear (Hooke's law) and non-linear lastest Duncan-Chang Hyperbolic Model to study the structural response of the dam in respect to the deformation and stresses of Main Dam of Bakun's Concrete face Rockfill Dam (CFRD) project which is currently under construction located in Sarawak, Malaysia as the second highest CFRD in the world when completed. Dead, Birth and Ghost element technique was used to simulate sequences of construction of the dam. The comparison of rigid and flexible foundation on the behaviour of the dam was discussed. In the finite element modeling the concrete slab on the upstream was represented through six-noded element, while the interface characteristic between dam body and concrete slab was modeled using interface element. The maximum settlement and stresses of the cross section was founded and the distribution of them were discussed and tabulated in form of graphs and contours. The effect of reservoir filling loading have gradual effect to the dam response behavior. The computed results by the present method were found to be in good agreement with the comparison of value to the existing dams in the world.

PENILAIAN KESELAMATAN EMPANGAN BATUAN BERPERMUKAAN KONKRIT BAKUN

Oleh

HILTON @ MOHD HILTON BIN AHMAD

ABSTRAK

Kajian ini merangkumi analisis unsur terhingga 2-dimensi terikan dasar linear kenyal (hukum Hooke) dan Model tidak linear Hiperbola Duncan-Chang untuk mengkaji reaksi perlakuan struktur empangan terhadap anjakan dan tegasan. Untuk struktur utama projek Empangan batuan berpemukaan konkrit (CFRD) di mana pada masa ini masih dalam proses pembinaan yang terletak di Sarawak, Malaysia sebagai CFRD yang kedua terbesar di dunia apabila siap kelak. Teknik unsur Dead-Birth-Ghost digunakan untuk memulakan turutan pembinaan empangan ini. Perbandingan antara perlakuan empangan ini dengan asas dan tanpa asas terhadap perlakuan empangan ini juga dibincangkan. Dalam model unsur terhingga, papak konkrit pada sebelah hulu empangan diwakili oleh unsur enam-nod, manakala ciri antara-muka empangan and papak konkrit dimodelkan menggunakan unsur antara-muka. Anjakan dan tegasan maksimum untuk keratan rentas empangan telah diperolehi dan pengagihannya telah dibincangkan dan digambarkan dalam bentuk graf dan kontur. Kesan bebanan daripada tadahan air mempunyai kesan terhadap reaksi perlakuan empangan tersebut. Keputusan yang diperolehi mempunyai persefahaman yang baik dengan perbandingan keputusan daripada empangan yang sedia ada.

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INTRODUCTION

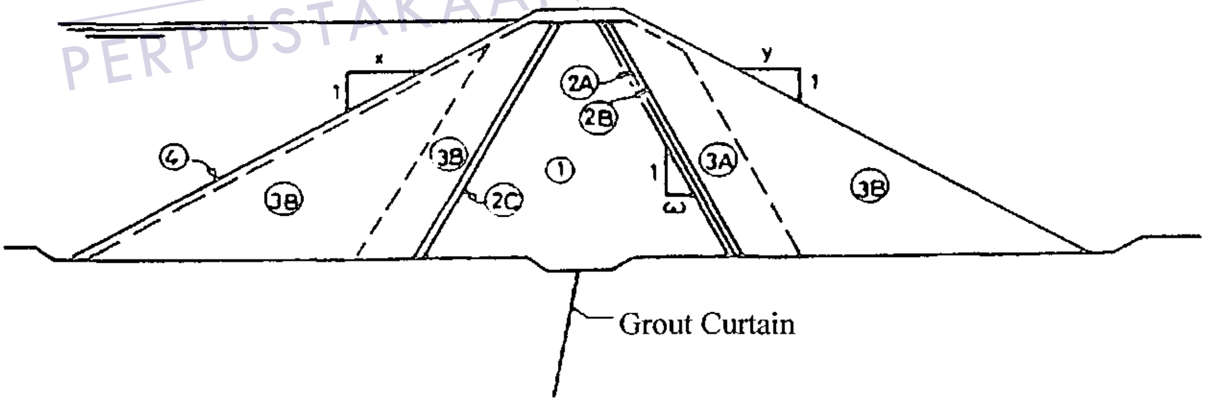
Malaysia, which comprises Peninsular Malaysia, Sabah and Sarawak. is located between latitudes 1° and 7° North and longitudes 100° and 119° East. It covers a total land area of over 330,000 km^2. With rapid population growth and accelerating economic development, much of the world's natural resources are being depleted at an unsustainable rate. One of these resources is WATER which requires urgent attention to ensure sustainable use.

Dams form part of a controlled irrigation system but they also have other roles to play, i.e. flood control, hydroelectric power generation and also as soil conservation. There are a few factors need to be taken care of when designing a dam, i.e. safety, economy, efficiency and appearance. Safety and economy are factors that contradict to each other; however, we may design an economical dam without sacrificing the safety of the dam. In this report, Bakun Dam which is the second biggest Concrete Faced Concrete Dam (CFRD) in the world when completed is analyzed to its safety by using finite element method. Dam structure often store huge quantity of water at great potential energy and if in the case of failure does pose an imminent threat to population and property downstream. There are many cases reported due to dam failure and it cause very severe damages.

Dams are designed to withstand all applied loads, e.g. gravity load, hydrostatic, hydrodynamic pressures etc. The biggest loads on dam are the gravity load due to its massive self weight and also earthquake loads. The accuracy of the estimation of dam safety under static and earthquake (dynamic) and the design work require a good understanding of structural response of dam under both cases. As far as the design aspect concerns, static load and dynamic load are contradicts as in static we need to design the stiffest structure, however, in dynamic it is required to design the structure most flexible. Therefore, the engineers should be aware of both criteria and fulfills to its optimum dam design.

1.1 <u>Development of Rockfill Dam</u>

In first half of 20th century, most rockfill dam were of loosely dumped quarried rock with some version of core or upstream facing including wooden planking, concrete, or hand-placed rock dry-wall as well as only few impervious core rockfill dams was built prior to the 1940, (Maranha,1991). Leakage due to high fill deformation and opening of the joints in these types of dams has become obvious. From thence up until the 1950's, the design and construction of rockfill dams were a matter of empiricism. Then, dam engineers diverted towards the earth core rockfill for the following 20 years.



1 Earthfill
2A Fine filter (or filter drain)
2B Coarse Filter layer
2C (i) Upstream filter
(ii) Filter under Rip Rap
2D Fine Cushion
2E Coarse Cushion layer
3B Coarse Rockfill

Figure 1.1: Types of Earth and Rockfill Dam with Core. (Robin et al., 1992)

The transition to compacted rockfill for both earth-core and concrete-face dams occurred during the period 1955-1965 (Cooke 1984) as shown in Figure 1.2. This transition was possible because of the advent of heavy rollers and was particularly spurred Terzaghi's criticism of dumped rockfill for its excessive compressibility as well as more compatible with the needs for an impervious concrete membrane. Comparison between rates of post-construction at the crest settlement between dumped and compacted rockfill are shown in Table 1.1

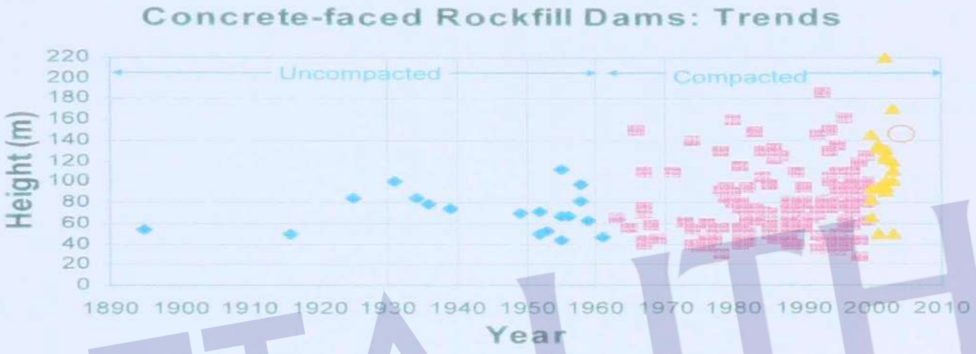


Figure 1.2: Trends in CFRDs over the past years

Table 1.1: Rates of post-construction crest settlement of dumped and compacted rockfills in CFRDs (Sherard and Cooke, 1987)

	Approximate Rate of Crest Settlement for 100m High CFRD (mm/year)		
Type	**After 5 years**	**After 10 years**	**After 30 years**
Compacted Rockfill	3.5	1.5	0.6
Dumped Rockfill	45	30	10

The leakages has been controlled to very reasonable levels, gradually the concrete faced rockfill dam (CFRD) resumed its place among rockfill dams. In this type of dam the foundation requirements being essentially the same as for the central core dam, other attributes such as simpler construction logistics, less cost, more compact layout, easier river handling solutions, shorter construction time, have been weighing in its favor. (Maranha, 1991) and (Robin et al., 1992).The cross section of concrete faced rockfill dam is shown in Figure 1.3.

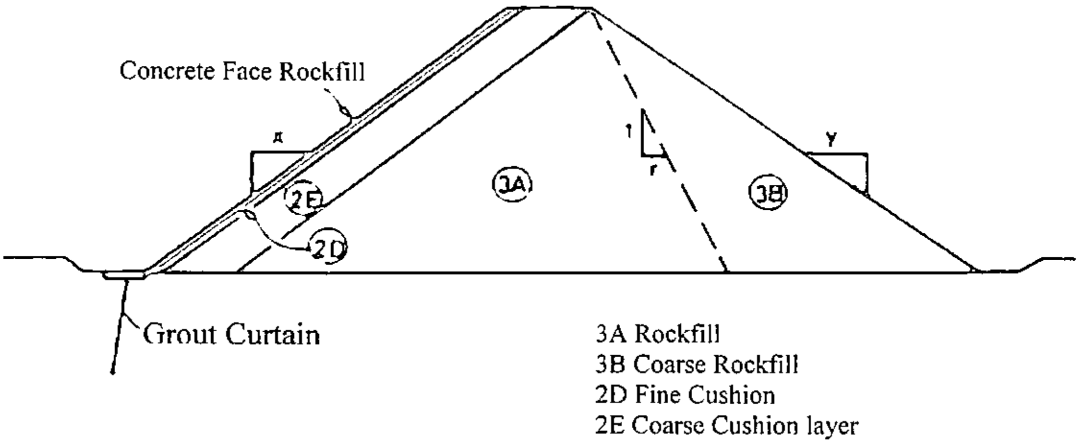


Figure 1.3: Type of Concrete Face Rockfill Dam (Robin et al., 1992)

Since dams are considered to be as mega projects, and infrastructures for any nation, hence, many international organization (International and National Commission on Large Dams (ICOLDS)), are involved in the documentation data of the concrete faced rockfill dam which was designed and constructed. After the evaluation of their implementations and operations, the legislation and guidelines on dam safety are issued, accordingly, to be followed by the owner of dams, consultants and construction dam industries. The history of CFRD development are tabulated in Table 1.2.

Table 1.2: Historical summary of rockfill usage in embankment design (Galloway 1939, Cooke 1984, Cooke 1993).

Approximate Time Period	Method of Placement and Characteristics of Rockfill	Comments
	Concrete Face Rockfill Dams	
Mid to late 1800's to early 1900's	Dumped rockfill with timber facing	Early embankments constructed with timber facing. Typically of very steep slopes (up to 0.5 to 0.75H to IV). First usage of concrete facing in the 1890's. Height limited to about 25 m.
1920's to 1930's	Main rockfill zone dumped in high lifts (up to 20 to 50 m) and sluiced, although the sluicing was relatively ineffective. A hand or derrick placed	Rockfill typically sound and not subject to disintegration. Dam heights reaching 80 to 100 m. For high dams, cracking of the lacing slab and joint openings resulted in high leakage rates (2700 l/sec Dix River, 3600
Late 1930'sto 1960's	High pressure sluicing used for the main rockfill zone. Rockfill still very coarse.	Cracking office slab, particularly at the perimeter joint, and high leakage rates a significant issue with higher dams (3100 l/sec at Wishon, 1300 l/sec at Courtright).
From late 1960's	Rockfill placed in 1 to 2 m lifts, watered and compacted. Reduction in particle size. Usage of gravels and lower strength rock.	Significant reduction in post-construction deformations due to low compressibility of compacted rockfill Significant reduction in leakage rates; maximum rates typically less than SO to 100 l/sec. Continued improvement in plinth design and facing details to reduce
	Earth and Rockfill Dams	
1900 to 1930	Dumped rockfill	Use of concrete cores with dumped rockfill shoulders at angle of repose. Limited use of earth cores. Dam heights up to 50 to 70m
1930'sto 1960's	Earth core (sloping and central) with dumped rockfill shoulders.	Use of earth cores significant from the 1940's due to the difficulties with leakage of C'FRD. Increasing dam heights up to 150 m.
From 1960's	Use of compacted rockfill. Typically placed in 1 to 2 m lifts, watered and compacted with rollers.	Improvements in compaction techniques. Early dams compacted in relatively thick layers with small rollers. Gradual increase in roller size and reduction in layer thickness reduced the compressibility of the rockfill. Significant increase in dam heights in the mid to late 1970's, up to 250 to 300 m.

CFRD is being recognized as one of the best choices among the dam consultants and engineers for its advantages. A list of several CFRDs which are already completed or still under construction, in the world is tabulated in Table 2.1.

1.2 Identified Problems

Up to date, a common assumption in modeling soil-structure interaction by earlier researchers and particularly, CFRD researchers is that they simulated their program with the foundation as rigid foundation (boundary fixation at the base of the dam), which leads to ignoring differential ground motions and its effects to the dam. This reduces the complexity of the problem (i.e. the number of additional degrees of freedom for accounting for the interaction), and make it possible to present general results. However, this does not present the actual situation, where a dam must rest on the foundations. Therefore, this study will include the effect of foundation (flexible foundation) with infinite elements.

As the actual instrumentation data are difficult to obtain due to certain circumstances, comparison of obtained results with the actual data cannot be done. The results are only been compared based on the results and observations by the previous researchers. The comparison is achieved by comparing different height, dimensions, shape of contours obtained, reasonable values of parameter being studied such as deformation and stresses.

At the initial period of analyzing Bakun Dam, I face difficulties in analyzing proper results for certain parameters. It is because of the Finite element analysis programme (Fotran) used does not considers certain elements, especially face slab elements. However, with some modification by eliminating certain criteria by the experts, it runs successfully. The results obtained are reliable since it shows patterns acquired of analyzing the dam with foundation compared to rigid foundation. Therefore, it is important to be aware of the limitation of the program provided.

1.3 Objectives of Research

The main purpose of this research is to study the structural response of 205m high Bakun Dam with concrete face due to static load by simulating finite element principles. The type of load is identified, and analysis is done based on the loads specified. This research also compares the analysis of Bakun Dam in two cases i.e. Main Dam with rigid foundation as well as with flexible foundation. The study of structural response of the dam is based on deformation and stresses which is the principal safety evaluation of Bakun Dam structure. The specific objectives of this project are listed as follows:-

a. Findings of a literature review to identify problems and uncertainties.

b. By using provided 2-D program, the study of structural response of Bakun CFRD is being done. The program has the following features:-

   (i) Simulation of Birth, Dead and Ghost element technique

   (ii) input parameters for the material linear and non-linear

   (iii)contact between any different material represent interface behavior

   (iv) simulation of loading during dam construction and reservoir filling

c. To analyze the relation between dam structure and also soil media (thus known as flexible foundation), then compares with analysis with rigid foundation,

d. To study the structural behaviour and safety of the dam from results obtained from static load cases of linear and non-linear analysis.

e. Study the sequence of construction as well as reservoir fillings based on ghost, birth and dead element techniques by using provided finite elements program.

f. To determine and study the face slab response to the dam as this is the most crucial section on CFRD as it always forms leakages and cracks.

1.4 Scope of study

The scope of study under this project is to analyze the behaviour of Bakun Dam in non-linear for both static and dynamic analysis. The study has been carried out within the following scope:

(i) By browsing previous research in journals and books of designing CFRD and their findings of the dam which covers the static linear and non-linear analysis. Then, by considering better results, some justifications are made.

(ii) Modeling and dicretizes of actual dimensions of Bakun CFRD based on finite element principles.

(iii) Verification of program is done based on experimental data available by previous researchers on their published papers.

(iv) Simulation of sequence in construction by using Dead-Birth-Ghost techniques which similar to the actual construction.

(v) Study the structural response of Bakun CFRD and the analysis is presented as follows:-

- ✓ Displacements (Horizontal and Vertical)
- ✓ Stresses (Normal stresses, σ_x and σ_y , and shear stress, τ_{xy})
- ✓ Principal stress (P_{max} and P_{min}) for non-linear analysis

There are 2 cases being investigated for each analysis above:

- o Without Foundation (Rigid Foundation)
- o With Foundation (Flexible Foundation)

Presentation of analysis will be in form of:-

- ✓ Graphs
- ✓ Contours

1.6 Organization of Thesis

In this project, the reports are arranged accordingly to give basic understanding in using the finite element programming used to analyze Bakun Dam. There are divided into chapters as follows:-

Chapter 2: Literature Review

This chapter gave basic idea of CFRD dam and illustrates the common CFRD dam section which described each section schematically. The previous investigations prior to this project on CFRD dam analysis for both static and dynamic loading are also described. This is important since we can predict the common behavior of most CFRD.

Chapter 3 to 5 represents the fundamental and principle used in analyzing Bakun Dam by using Fotran finite element programming.

Chapter 3: Fundamental and principal of Finite Element Method.

This chapter described from the basic fundamental in finite element. However, the emphasized to the 2-D strain plane element, by which Bakun Dam are idealized. Dynamic and non-linear approaches to finite element are also described.

Chapter 4: Constitutive Law for Soils

For this chapter, since the model used in the analysis of non-linear is "Duncan Model", his model is described in details in this chapter. The equation of non-linear properties which is used in analyzed the dam is also highlighted. Sample of calculation are also given.

Chapter 5: Bakun Dam Analysis

Chapter 5 presents the results of finite element analysis Bakun CFRD models in linear and non-linear analysis with respect to deformation and stresses. The results are discussed in details and comparison is made due to previous findings as well as theory.

Chapter 6: Conclusions and Recommendations

The last chapter which gave the summary of results and overall study. The recommendations for future research are also being proposed here.

LITERATURE REVIEW

2.1 Introduction of Dam

Dams can be defined as a watertight structure that is build across a river and to create a reservoir at the upstream of the dam. A dam is an obstacle built across a river or a lake to hold backwater. The reservoirs that form behind them are used to store water and for four major functions: Water supply, hydropower, flood control and new tourist attraction. A dam can perform more than one of these functions.

Figure 2.1: Type of Dams (a) Embankment dam (b) Concrete Dam (c) Arch Dam

The type and size of dam are dependent upon the geology, hydrology and topography of the site. Furthermore, the construction materials which are readily obtainable. Rockfill dam which is falling under embankment dam are as follows:-

a) Composite Earth and Rockfill Earth core is one of the watertightness material are used in membrane zone. This can be placed in central, sloping or upstream of a rockfill dam which shown in Figure 2.2, Figure 2.3 and Figure 2.4.

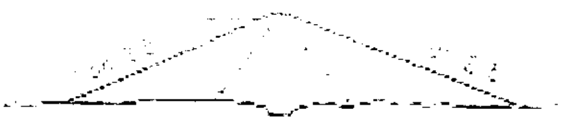


Figure 2.2: Central earth core.

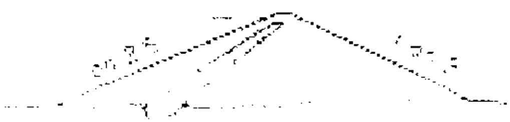


Figure 2.3: Sloping earth core.

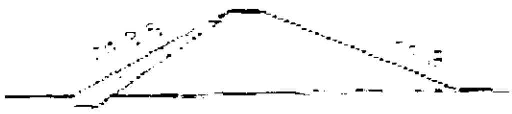


Figure 2.4: Upstream core.

b) Rock with Thin Membrane This membrane can be either steel sheet pile or composite material that is shown in Figure 2.5

Figure 2.5: Central thin membrane.

c) Faced or Impervious Membrane Type An impervious membrane for water tightness was placed on the upstream slope. Concrete faced is most widely used for rockfill dams, followed by bitumen, asphalt, wood, steel, dry rubble masonry or stone masonry. Figure 2.6 shown that the concrete faced rockfill dams.

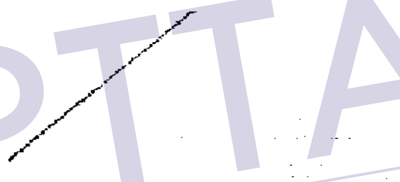


Figure 2.6: CFRD (Black line represents concrete or bitumen face)

2.2 <u>Concrete Faced Concrete Dam</u>

A major recognition to the development of CFRDs is given to Chinese Engineering, where dam construction has reached values exceeding the rest of the world. China has started CFRD dam construction using modern technology since 1985. By 2004, there are more than 164 CFRD with height over 37m completed and 37 are height over 100m. The highest one completed is 179.5m high Hongjiadu CFRD and the highest one under construction is the 233m high Shuibuya CFRD which expected to be completed in 2009. Their most contribution on CFRD development are the development of articulated plinths on alluvium and the necessity to incorporate vertical and horizontal drains in sand gravel dams, when the permeability is affected by the amount of fines.

The process of CFRD construction also includes a lot of research achievement need to be obtained in the field layout, besides the accumulated practical experience. Among the research achievement needs to achieved are listed as follows:-

- Structure of dam embankment and dam materials
- Static and dynamic three-dimensional finite element analysis
- Geotechnical centrifugal tests
- Face slab concrete
- Water sealing structure and materials,
- New construction technologies
- Instrumentation and analysis of observation.

The evolution of CFRD during the past 30 years has had an important influence on design and construction methods. Some aspects of design change when the height of the dam increases has motivated designers and contractor to develop innovative construction methods increasing productivity.

2.2.1 Overview of design and construction of operational (completed) CFRDs

(i) Centhana dam, Australia.

The 110 m high Centhana Dam was highest well-compacted CFRD from 1971 – 1974. The practical design recommendations opened the door for higher dams developed in the 1970s. Centhana's performance was excellent, and the sound criteria for compaction and face design are still being applied in dams of similar height.

(ii) <u>Alto Anchicaya, Columbia</u>

Alto Anchicaya, 140m high, was the highest CFRD from 1974 to 1980. This dam was very well compacted, and the face slab was constructed, for the first time, in two stages using multiple slip forms. It emphasized the importance of providing multiple defenses at the perimetric joint when some leakage was detected. This was well treated by placing mastic over the joint. Since then, more dams have used mastic as a complementary protection. Aside from the leakage problem, the behaviour of the dam has been satisfactory.

(iii)<u>Foz do Areia, Brazil.</u>

This dam is 160m high, was the highest CFRD from 1980 to 1993 and the first CFRD in Brazil. An special zone under the perimetric joint was used and mastic was designed over this joint. Ramping and construction stages were widely applied for the rockfill and face slab construction was built in two stages. The performance of this dam has been excellent after 24 years of operation.

(iv) <u>Salvajina Dam, Columbia</u>

At 148m high, Salvajina dam is one of the highest gravel dams built in seismic area. The concept of plinth design was adjusted to the geology, which varied from saprolite to fresh sandstone. Plinth gradients were defined for the different types of foundation. The perimetric joint was designed with copper water stop and mastic. Face slab was constructed in three stages and double parapet was designed for reducing dam volume. The upstream slope was treated with shotcrete and some minor cracking and spalling was observed. Copper waterstop was placed directly at the dam site, reducing welding. Salvajina dam showed that dense quaternary deposits may remain in the dam and that compacted gravel is remarkably less compressible than the compacted rockfill. Leakage was nominal, and the performance of the dam has been satisfactory.

(v) Tian Shen Qiao, China.

At 178m high, Tian Shen Qiao is the highest CRD in operation in Asia and second highest in the world. For the first time in CFRDs, the rockfill placement exceeded $1Mm^3$/month, demonstrating the construction advantages of this type of dam. Horizontal cracks were detected in zone 2 and face slab, which were well treated. Tensile strains due to rockfill creep were causing these cracks. The performance of the dam is satisfactory and the leakage nominal for the height and face slab area.

2.2.2 Overview of design and construction of under construction CFRDs

(i) Bakun Dam, Malaysia.

Located in Borneo with height of 205m, it will be World's second highest when completed. Bakun is being designed with all the modern concepts for external and internal plinth, extruded curb, face slab, parapet and very well compacted fill. The dam will be built with Greywacke and adequate mixtures of Greywacke and shales. The priority section for protecting the dam against 1:500 year floods is under construction.

(ii) Karahjukar Dam, Iceland

The 196m high Karahjukar will be Europe's highest CFRD when completed. The dam is very well compacted in layers, varying between 0.4m (zone 2) and 0.8m, by vibratory roller, 12 tonne capacity. The unique canyon of the river, 45m deep required a solution with a concrete dam, where the plinth is located. Karahjukar Dam has adopted all the new concepts of design for the plinth, face slab and reinforcement of critical zones.

(iii) <u>Shuibuya Dam, China</u>

Shuibuya, at 233m high, will be the highest CFRD in the world when completed. It currently stands at 170m high, with the first stage of the face slab having been completed. Fill control is being applied using modern techniques based in GPS control.

Table 2.1: World's highest existing CFRD.

Name of Dam	Country	Year Of Completion	Height (meter)
Aguamilpa	Mexico	1993	187
Tianshengqiao	China	1997	180
Foz deArera	Brazil	1980	160
Xingo	Brazil	1994	150
Salvajina	Colombia	1983	148
Segredo	Brazil	1991	145
Alto Anchicaya	Colombia	1974	140
Chuza	Colombia	1978	135
Messochora	Greece	1994	135
Koman	Albania	1986	133
New Exchequer	USA	1966	130
Golillas	Colombia	1978	130
Khao Laem	Thailand	1984	130
Shiroro	Nigeria	1984	130
Cirata	Indonesia	1987	125
Reece	Australia	1986	122
Neveri	Venezuela	1981	115
Paradela	Portugal	1958	110
Rama	Yugoslavia	1967	110
Cethana	Australia	1971	110
Batang Ai, Sarawak	Malaysia	1985	110

2.3 Dams in Malaysia

In Malaysia, there are more than 50 of dams which being built since the British colonial. Figure 2.1 shows the location of dams in Malaysia that being developed and controlled under Drainange and Irrigation Department (DID) and Tenaga Nasional Berhad (TNB). Most dams built since 1990 or currently under design are more complicated in type, compared to existing old dams. CFRD (Concrete Faced Rockfill Dam) and RCD (Roller Compacted Concrete Dam) are good examples of these types. Especially, in case of CFRD, the number of its construction has been increasing and been favors in new dam construction. There is only one completed large-scale dam that had been constructed before 2000 are in CFRD type (Batang Ai Dam, Sarawak).. And, as of now, in the year of 2005, three (including Bakun Dam which is still under construction) irrigation and power-plant dams are being constructed in CFRD type. As the number of CFRD constructions increases, the necessity of an accurate assessment on its construction behavior also has been increasing accordingly. But, our domestic research on CFRD construction behavior has yet been insignificant.

Figure 2.7: Location of Major Dams in Malaysia.

2.3.1 CFRD dams in Malaysia

Currently, there are more than 35 existing dams for irrigation purposes (which operated by the State Water Authorities and Public Works Department) and about 9 dams for hydropower generation (owned by Tenaga Nasional Berhad, TNB) in all over Malaysia. There are few more dams is still under construction). Total of these figures, only 3 dams are falling under CFRD category. There are Beris Dam (in Kedah), Batang Ai Dam (in Sarawak) and Bakun Dam (in Sarawak, under construction). The location of each dam is illustrated in Figure 2.8.

The Batang Ai Hydroelectric station is the first major hydroelectric station in Sarawak. The station incorporates the highest man-made rockfill dam and the biggest man-made lake in the state. It has an installed capacity of 108 MW and generates an average energy output of 614 MW annually. The station is located about 18km upstream of Lubok Antu, Sri Aman. It is about 274 km by road from Kuching. The station consists of a Main Dam, three saddle dams, a power plant of 4 x 27 MW vertical Francis Turbines ad generators. The main Dam and Lima Saddle Dam are of CFR embankment. The maximum height of the main dam is 85m above its foundation and that of the lime Saddle Dam is 60m. Construction of the station started in 1981 and was completed in 1985. The Batang Ai was diverted in July 1982 and impounded of the Batang Ai Reservoir was carried out in October 1984.

Beris Dam located in a narrow valley of Beris River 1.6km upstream of the confluence between Muda River in the district of Sik, in the state of Kedah. It is completed at 300million in September 2003 and used to regulate flows in

Muda River basin to augment water available for irrigation of paddy/upland crops, domestic and industrial water supply and other uses. The reservoir at its normal pool level will inundate an area of 16.1km2. It will have a gross storage capacity of 1224Mcm with an effective storage of 144Mcm.

Bakun Dam HEP was proposed as part of a series of dams to exploit the hydroelectric potential of Sarawak river. It was to comprise the construction of 2400 MW hydroelectric dam with massive 205 metre high CFRD. It was described in details in Chapter 5.

Figure 2.8: Map of Location of CFRD dams in Malaysia

Batang Ai, Sarawak	Beris Dam, Kedah	Bakun Dam, Sarawak
(completed in 1985)	(completed in 2003)	(expected to complete in 2009)

Figure 2.9: CFRDs in Malaysia.

2.3.2 Seismicity in Malaysia

Malaysia is closed to the most two seismically active plate boundaries, the inter-plate boundary between the Indo-Australian and Eurasian Plates on the west and the inter- plate boundary between the Eurasian and Philippines Sea Plates on the east. Major earthquakes originating from these plate boundaries have been felt in Malaysia.

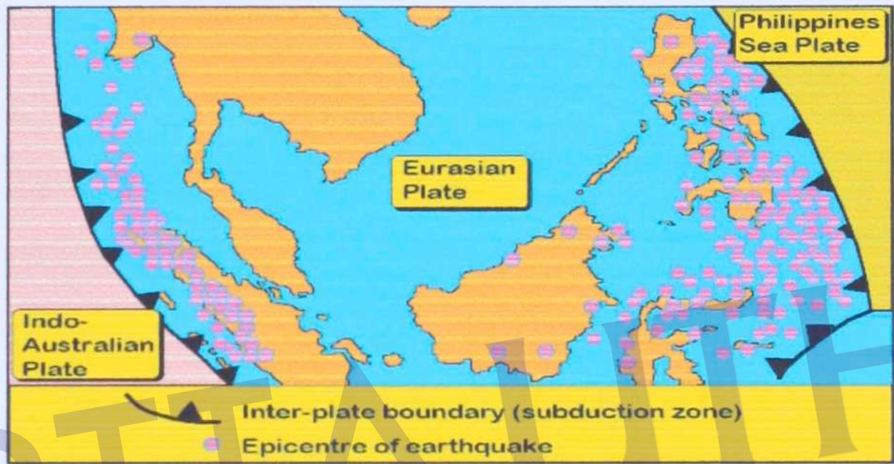


Figure 2.10: Plate boundaries and epicentral distribution

Tremors felt along the west coast of Peninsular Malaysia are originating from large earthquakes in the active seismic areas of Sumatra and Andaman Sea. East Malaysia has experienced earthquakes of local origin. Several possible active faults have been delineated and local earthquakes in East Malaysia appear to be related to some of them. In addition to the local earthquakes, East Malaysia is also affected by tremors originating from large earthquakes located over Southern Philippines and North Sulawesi. PGA values in Malaysia are given in Figure 2.11.

Table 2.2: Earthquake Felt in Malaysia

State	Frequencies	Maximum Intensity Observed (Modified Mercalli Scale)
Peninsular Malaysia (1909-2003)		
Selangor /Kuala Lumpur	27	VI
Johor	16	VI
Malacca	3	IV
Negeri Sembilan	2	II
Perak	11	IV
Penang	21	VI
Kedah	6	V
Perlis	1	I
Kelantan	2	III
Terengganu	Nil	Nil
Pahang	3	II
Sabah (1923-2003)		
Sabah	19	VII
Sarawak (1923-2003)		
Sarawak	3	IV

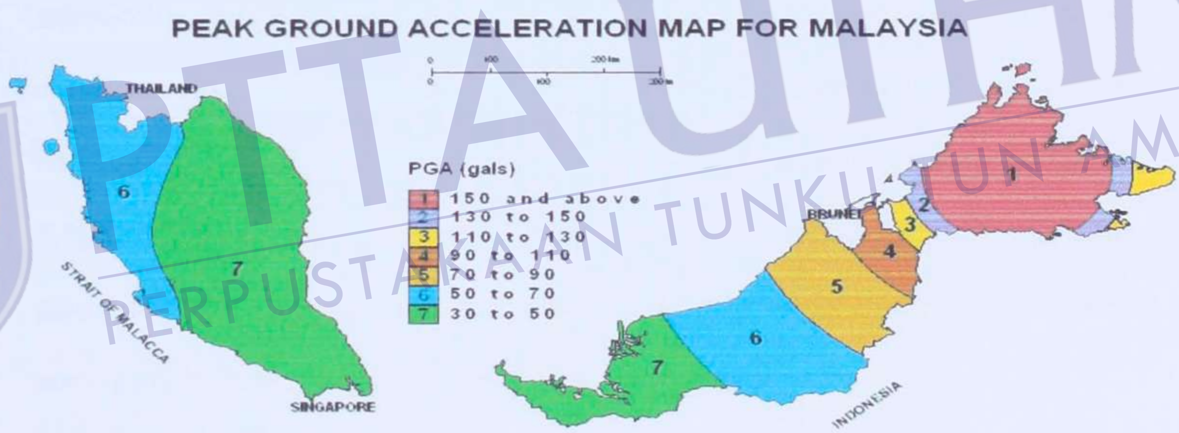


Figure 2.11: PGA map for Malaysia.

2.3.2.1 <u>Seismic Stability of Bakun CFRD</u>

As is known, strong earthquakes have occurred during the past 20 years in a number of regions of Latin America, Southeast Asia, in California, and Australia, including in regions of the location of CFRD dams which, however, did not lead to any damages. In connection with this, it is necessary also to note that even less reliable rockfill dams with concrete facings constructed before 1970s in California, Mexico, Chile, Yugoslavia, and Romania also withstood very strong earthquakes, including those with an intensity of 8 – 9. Thus, for example, the 84m high Cagoti Dam with a multilayer facing constructed in Chile in 1939 safely withstood a strong earthquake in April 1943 (acceleration of the foundation 0.3g, magnitude 7.9 – 8.3) without any signs of cracks in the facing (the settlement of at crest was 42 cm).

Bakun CFRD is located in an area of low to very low natural seismic activity. This is confirmed by the fact that only twelve tremors have been felt in the area in the last 100 years. The project area is located in a stable block far from the seismically active plate boundaries. The seismic hazard assessment indicates that the maximum credible event (an event of Modified Mercalli Intensity I-VII) for the site would generate a peak ground acceleration (for design purposes) corresponding to 0.1g (gravitational pull). Modern CFRDs can safely withstand the ground shaking associated with accelerations higher than this. In conclusion, seismicity at the site does not constitute a safety issue nor a major design issue.

Although the dam and reservoir are both very large, the probability that the project might trigger an earthquake is small because of the low natural seismicity of the area, and the watertightness of the reservoir. Even if an earthquake were triggered by the reservoir, that event will occur within the framework of the pre-existing low seismic activity. Any reservoir-triggered earthquake will be smaller than the maximum naturally occurring earthquake discussed above. Occurrence of an earthquake would tend to cause small settlements of the dam. Although no modern

CFRD has been subjected to strong earthquake shaking, Cogoti Dam, in Chile, an earlier dumped rockfill CFRD experienced shaking generated by a large (magnitute 8.3) earthquake centred 16 kilometres away from the site. The dam settled 38 centimetres at the crest. No damage of significance was experienced. The earthquake shaking experience at Cogoti greatly exceeds the ground movements that might be expected to occur at Bakun during an earthquake.

A modern well-compacted CFRD, such as Bakun, undergoing an earthquake would experience smaller settlements that would not endanger the stability of the dam. Several high CFRDs have been constructed in areas of moderate to high seismicity. Of the above, only Foz do Areia, Brazil, is in an area low seismicity similar to Bakun. These CFRDs have been designed and constructed using many of the defensive measures discussed above.

Table 2.3: List of CFRDs in Seismic Areas

Dam	Height (metre)	Seismicity of Site
Bakun, Malaysia (u/c)	205	low
Sogamoso, Colombia (u/c)	195±	moderate to high
Aguamilpa, Mexico	187	high
Tiangshengqiao, China	180	moderate
Foz do Areia, Brazil	160	low
Messochora, Greece	150	moderate
Salvajina, Colombia	145	moderate
Alto Anchicaya, Colombia	140	moderate
Golillas, Colombia	130	moderate
Cirata, Indonesia	125	high

Note: u/d = under design; u/c = under construction

2.4 Basic Feature of CFRD dam

The basic features of the CFRD are outlined in Fig. 2.12. Compared to the earth-core rockfill dam (ECRD), the main body of the CFRD consists exclusively of rockfill, all of which is located downstream from the water thrust; the latter acts externally on the upstream reinforced-concrete face and contribute to increasing the stiffness and stability of CFRD. Hence, much steeper slopes (ranging from 1:1.3 to 1:1.6) are attainable in CFRD.

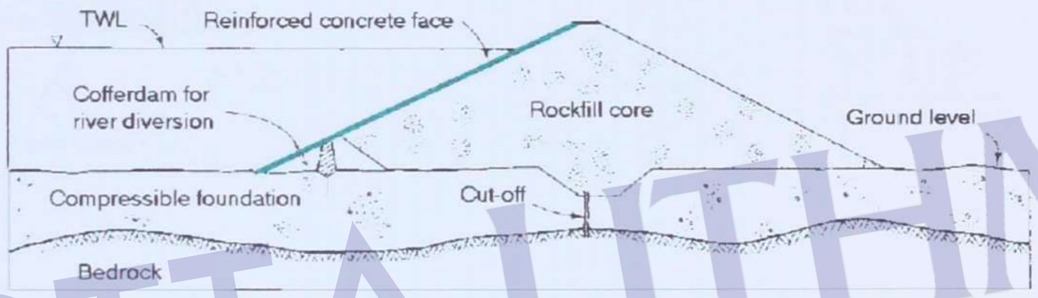


Figure 2.12: Typical structure of CFRD

Figure 2.13 shows the cross-section and some characteristic details of a typical design. Compaction of the rockfill to a high density is required for minimizing deformations and face-slab distress and leakage. High moduli of deformation have in fact been achieved in CFRDs with rock fill having uniformity coefficient of 20 or higher and containing about 30% of material smaller than 1 in (25.5 mm). Measurements have also shown that rockfill is about three times stiffer in the horizontal than in the vertical direction due to high shear rockfill, no pore pressures in rockfill, small settlement of rockfill under seismic load. This make CFRD resistant to seismic loading

Water load are transmitted into foundation upstream of dam axis. Unlike gravity dam, uplift under rockfill is not required. The pressure on the foundation exceeds reservoir pressure over ¾ of base width. Therefore, drainage galleries in abutments are not required. Sliding factor for reservoir water and rockfill exceeds 7. Overtopping can cause failure to CFRDs.

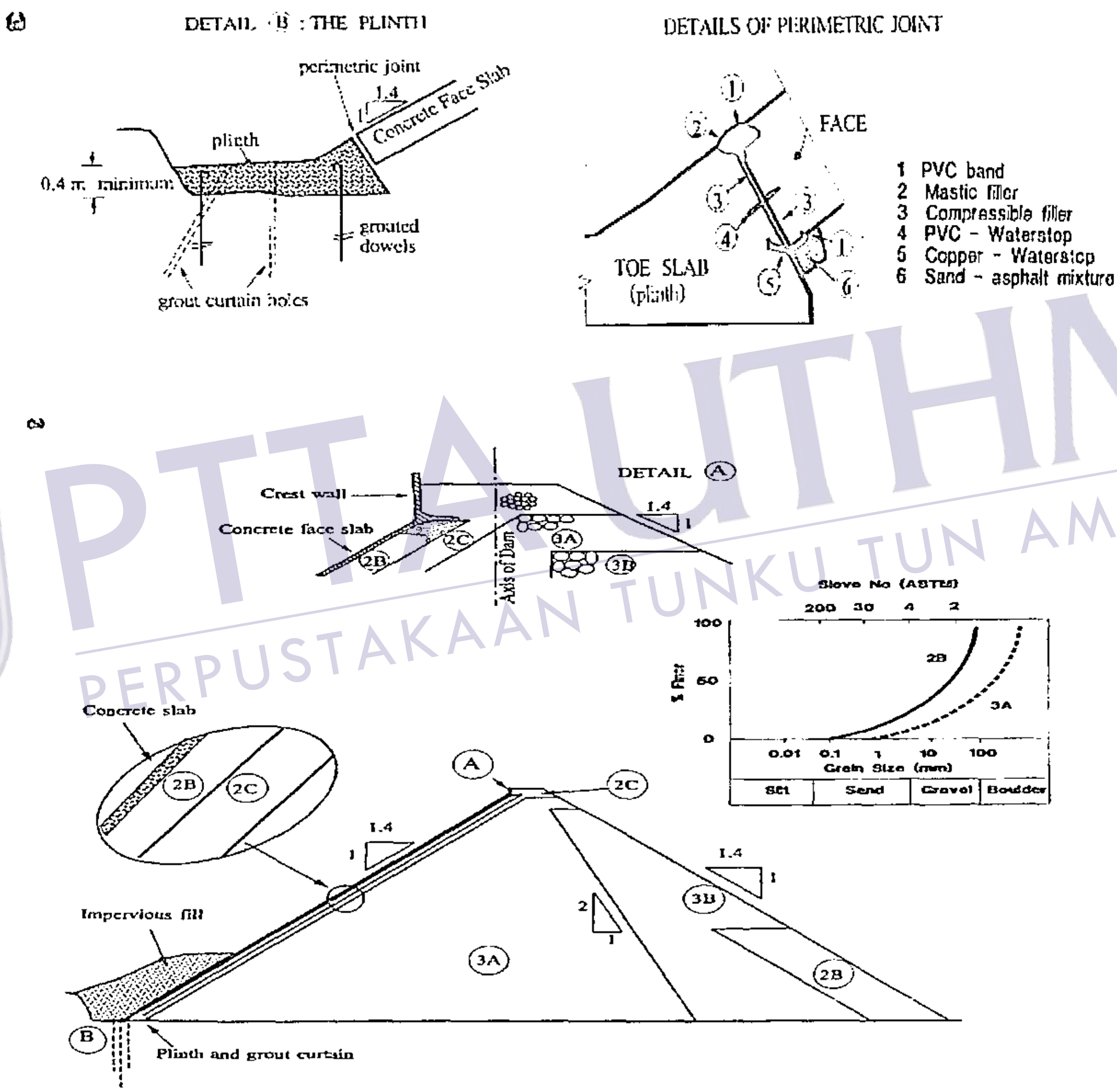


Figure 2.13 (a): Cross-section and detail of the `plinth' and perimetric joint.

(b): Typical cross-section, details of the crest and material composition of a CFRD.

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