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THE ASPHALT CORE EMBANKMENT DAM: A VERY COMPETITIVE ALTERNATIVE

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Abstract: The asphalt core embankment dam is gaining in popularity as the advantages of this design become more apparent. Countries like Austria, Germany, China and Norway, among others, have built many of this type of dam over the last 50 years, and now new countries like Brazil and Canada are building their first ones. A summary of recent research results and case studies is presented. Laboratory tests have demonstrated the high resistance of asphalt concrete to earthquake shaking. The self-healing (self-sealing) of any cracks that may occur due to accidental loads has been demonstrated to take place very quickly. The requirements to asphalt aggregate quality do not have to be as strict as those practiced for asphalt concrete in pavement construction. This opens up the possibility for using aggregates available locally, and there is no need to transport aggregates over long and costly distances to meet the strict pavement criteria. Field experience and special field tests have demonstrated that the rate of construction of an asphalt core can be increased considerably compared to previous practice without reducing the core quality. The core may be built in rainy and cold weather, and the core construction will not slow down the construction of other zones of the embankment. Field case studies also confirm that asphalt core dams may be successfully built with lower grade compacted rockfill than that usually required in earlier dams of this type. The dam may be built over compressible foundations as the core, due to its ductile and viscous behavior, can accommodate differential foundation settlements without cracking. The difference between the stress-strain behavior of laboratory- and field compacted specimens, even with the same air porosity, must be recognized and accounted for in the quality assurance and control program during construction. The differences are discussed, and a method of laboratory compaction has been developed that best simulates the field roller compaction for an asphalt core.

A comparison is made among embankment dams designed with concrete facing and asphalt core, pointing out relative advantages and disadvantages.

Key words: embankment dam; asphalt concrete core; case studies; research results; design alternatives.

1 Introduction and background

The first embankment dam with a compacted asphalt concrete core was built in Germany in 1961-1962, and Hydropower and Dams (2008[1]) provides a listing of asphalt core dams that have been built and are under construction in different countries. The International Commission on Large Dams (ICOLD) and others have summarized the experience with the design, construction and performance of this type of dam (e.g., ICOLD 1992[2]; Höeg 1993[3]; Creegan and Monismith 1996[4]; Schönian 1999[5]; Höeg et al. 2007[6]; Wang 2008[7]).

Most asphalt core dams have been built in Europe or by European contractors, but China has also built and is currently building several dams of this type, among them the 170 m high Quxue Dam which will be the highest so far. Canada just completed an asphalt core dam, the first of its kind in North America (Alicescu et al. 2008[8]), and Hydro Quebec has decided to construct several more embankment dams of this type in the Province of Quebec (La Romaine project). Brazil is currently building its first asphalt core dam (Foz do Chapeco), and Spain, Saudi-Arabia and Iran recently completed their first ones.

The paper presents the results from recent research, field experience and case studies and a discussion of the relative merits of different embankment dam design alternatives.

2 Recent research on asphalt concrete for embankment dams

Previous research and field experience have demonstrated that the properties of asphalt concrete may, within fairly wide limits, be tailored to satisfy specific design requirements. The quality control of the asphalt mix design and material properties is simple to carry out in the field laboratory and during field construction. Asphalt concrete can be made virtually impervious and flexible, is resistant to erosion and ageing, and it offers jointless core construction. The viscoelastic-plastic and ductile properties provide a self-healing (self-sealing) ability should cracks develop in the core wall due to differential displacements (shear distortions) caused by severe earthquake loading. Asphalt concrete is a very “forgiving” material in its behaviour relieving itself of stress concentrations. The use of softer bitumen than in previous construction increases the self-sealing quality and allows lower operating temperatures and energy input during material production, transportation and core placement. Among all the dams built, there is no case of reported leakage through an asphalt core.

2.1 Effects of earthquake loading

In the literature, only a few experimental studies have been performed to investigate the behavior of hydraulic asphalt subjected to cyclic loads simulating earthquake shaking (Höeg 2005[9]). Breth and Schwab (1973[10]) performed a cyclic direct shear test on an asphalt specimen simulating an element of the core inside an embankment dam and concluded that the imposed cyclic loading had no degrading effects on the properties of the asphalt concrete. That was the “state of the art” until Feizi-Khankandi et al. (2008[11]; 2009[12]) recently reported the results of cyclic triaxial tests to derive material parameters for the seismic analysis of the Garmrood asphalt core embankment dam in northern Iran.

Wang (2008[7]) systematically studied the effects of cyclic loading on the stress-strain-strength behavior and permeability of asphalt concrete. The author conclude: (1) the cyclic modulus versus mean static stress showed an approximately linear relationship in a logarithmic diagram; (2) the test temperature had a significant effect on the value of the cyclic modulus, as an example: at 1 MPa mean sustained stress the cyclic modulus at 20°C was approximately 900 MPa; (3) the number of load cycles had no significant effects on the magnitude of induced cyclic strain; and (4) the cyclic loading had very little degrading effect on the post-cyclic stress-strain-strength behavior and watertightness of the asphalt concrete.

The results show that the asphalt core in an embankment dam in a seismic region can withstand very severe seismic shaking without cracking and losing watertightness. The earthquake resistance of the dam will rather depend on proper design and zoning of the embankment itself, considering the available fill materials, the foundation conditions, and the seismicity of the site.

2.2 Effects of quality of aggregates used in the asphalt mix

In general, aggregates for asphalt concrete should be made of sound and property-stable rock. The aggregates should be clean and have suitable particle shapes (low flakiness index), surface texture and gradations. For good aggregate-bitumen adhesion, alkaline aggregates like limestone are usually required. In the past decade, acidic aggregates have successfully been used for road asphalt by using anti-strip additives to improve the aggregate-bitumen adhesion.

However, very little has been reported on the research of aggregate suitability for hydraulic dense grade asphalt concrete with air porosity less than 3%. A difference in aggregate strength has been documented to have little effect on the stress-strain-strength properties of hydraulic asphalt concrete (Höeg 1993[3]). For many dam projects, in remote areas, alkaline materials are not available locally, but only acidic materials such as granitic rocks which are strip-prone. The alternative to using the locally available strip-prone aggregates may be long transportation distances to get more suitable aggregates often at large extra costs.

An extensive series of laboratory tests was therefore performed to study aggregate-bitumen adhesion and its effects on asphalt concrete stress-strain-strength behaviour (Wang 2008[7]). The authors conclude from the study: for hydraulic asphalt with air porosity <3%, the permeability is so low with a significant bitumen film thickness covering the aggregate particles, that water immersion and freeze-thaw cycles have no effects on the compressive, tensile and bending strengths even when strip-prone aggregates are used. Therefore, it seems safe to use strip-prone aggregates in hydraulic asphalt without having to replace them with imported alkaline aggregates or to use adhesion-promoting measures like amine or hydrated lime.

2.4 Cracking resistance and self-healing properties

Fissures or cracks may tend to open up locally due to large shear stresses or tension stresses caused by loads, imposed displacements, or temperature changes. The strain levels at which cracks open depend on a number of factors, e.g. asphalt mix design, the loading rate (strain rate) and the temperature level. Wang (2008[7]) presents the results of a series of experiments and compares his findings with those previously docuneted in the literature.The results show that the magnitude of tensile strain that asphalt concrete can undergo (tolerate) before cracking occurs, can be significantly increased by using a richer asphalt concrete mix, softer grade of bitumen or by adding admixtures to improve asphalt concrete ductility.

If cracks do occur, asphalt concrete has self-healing (self-sealing) properties due to its viscous behavior. Wang (2008[7]) studied crack self-healing and the regaining of tensile strength using several different asphalt concrete mixes tested at various temperatures and stress levels. The crack self-healing was evaluated by measuring the rate of water leakage through specimens cracked by splitting.Within only a few hours, the rate of leakage dropped 2 orders of magnitude. The regained tensile strength of the cracked laboratory specimens was determined by performing tension splitting tests after the cracked specimens were self-healed under the vertical stress of 1.0 MPa for 24 hours at 7°C. The strengths of intact (no cracks) specimens were also tested by splitting. The average regained strength for three groups of three specimens each was found to be 55%. The unique self-sealing and self-healing ability of asphalt concrete may eliminate the need for remedial measures due to possible fissures and cracks caused by earthquakes and differential settlements in asphalt core embankment dams.

2.4 Increased rate of core construction without compromising core quality

If required, one may use significantly higher rates of asphalt core construction than previously practiced (i.e. two layers a day of 20 cm compacted thickness) without reducing the quality of the compacted asphalt concrete in the core. Tschernutter (1997[13]) reports that the maximum construction rate of the asphalt core for Feistritzbach rockfill dam was 3 layers a day (60 cm compacted). The air porosity in all specimens drilled out of the core was found to be less than 2.5%, meeting the conventional design requirement for asphalt cores of less than 3% air porosity.

Saxegaard (2002[14]) built a full scale 15 m long model test section of a dam core using asphalt concrete mix with 6.7% bitumen content (type B180) to test the effects of layer thickness and number of layers placed per day on the resulting core quality. In one case he placed four layers of 20 cm compacted thickness in one day (i.e.80 cm/day). In another case he placed three layers of 30 cm compacted thickness in one day (i.e. 90 cm/day). Test results of specimens drilled out of the compacted core showed air porosity less than 3% for both cases.

The Zhaobishan gravel embankment dam in China, 71 m high with an asphalt core of 64 m, is located in a narrow gorge. Due to the threat of flooding and overtopping during construction, the asphalt core had to be raised rather quickly. During the critical period of the first 67 days the construction rate was 70 cm/day for 25 days and 90 cm/day for 7 days.The air porosity of drilled core specimens was less than 3% (Wang et al. 2009[15]).

The latest systematic series of field tests on the effects of layer thickness and number of layers placed per day, are presented by Alicescu et al. (2008[8]) from the construction of Nemiscau-1 dam in Canada. They conclude that 4 layers of compacted thickness 22.5 cm may be placed per day, still maintaining high core quality with air porosity well below the required 3%.

2.5 Effects of difference between laboratory and field compaction methods

Wang and Höeg (2009[16]) used four different laboratory compaction methods, i.e. the Marshall, Vibration, Static and Gyratory methods, to investigate the effects of type of compaction method on the triaxial stress-strain behavior of asphalt concrete and compared it to that of asphalt concrete compacted in the field by a vibratory roller. Although the asphalt concrete specimens were all made of the same mix and compacted to approximately the same density (air porosity), the resulting stress-strain curves were very different. The secant modulus up to 1% axial strain for the Gyratory compacted specimens was 6 times that of the field compacted specimen, and the axial strain of the field specimen at failure was 6 times that of the Gyratory specimen.

A study was undertaken by the authors to determine the reasons for the differences among the specimens compacted by the various laboratory methods. The authors concluded that the differences in aggregate structure, grain skeleton arrangement and degree of interlocking achieved during the various methods of compaction explain the large differences in observed stress-strain behavior. Sawed sections through the specimens compacted by the different methods, support this explanation. It is the elongated and plate-shaped form of some of the aggregates that create the very significant skeleton structure effects, which will strongly depend on the method of compaction.

Considering the limitations of the conventional laboratory compaction methods, Wang (2008[7]) developed a new laboratory method and procedure to better simulate field compaction of hydraulic asphalt concrete in dam cores and facings. The new laboratory compaction is called the SC-method (Simulating field Compaction). The proposed SC-compaction method gives laboratory specimens with stress-strain behavior similar to that of field compacted asphalt concrete and may be used for mixes with all types of natural and crushed aggregates (Wang and Höeg 2009[16]).

The asphalt concrete barrier in hydraulic structures must exhibit flexible and ductile stress-strain behavior to be able to adjust to differential displacements or distortions in the embankment without dilation, cracking and increased permeability. Therefore, the field compaction must be adapted to the conditions and asphalt concrete mix used. Extra compaction effort will not necessarily lead to improved asphalt concrete properties and behavior. Over-compaction may lead to excessive aggregate skeleton interlocking resulting in stiff, possibly somewhat brittle, behavior of the material, which may experience cracking when the dam is deforming due to static and dynamic loads and differential foundation settlements.

3 Asphalt core dams do not require high quality rockfill

Tschernutter (1997[19]) presents the design and construction of the 85 m high Feistritzbach asphalt core rockfill dam. The main challenge proved to be that the available rock from the local quarry turned out to be much inferior to that anticipated during design. It was partly severely weathered and crumbled badly during processing. The poor rockfill resulted in embankment deformations at twice as large as originally calculated. The field observations and back-analyses show that the asphalt core followed all deformations of the embankment without any cracking, and it is virtually watertight.

Höeg et al. (2007[6]) present the Storglomvatn and the Holmvatn asphalt core dams which both, especially Holmvatn, have much lower quality rockfill than that used in previous dams of this type in Norway. The Storglomvatn Dam is 125 m high, and the saddle dam, Holmvatn, 56 m The upstream slope of the two dams built on rock foundations is 1V:1.5H, the downstream slope between the berms is 1V:1.4H. The quarry close to the Holmvatn dam contained meta sandstone with significant intercalated zones of mica schist/shale. During quarrying the schist from the quarry turned out to be of even poorer quality than anticipated in design, and some of the truck loads brought on to the dam had to be rejected. After vibratory roller compaction, the rockfill surface was in some cases so pulverized that the top layer was removed before the next lift could be placed. To reduce the breakage, the 15-ton roller initially specified was replaced by a lighter 11.7-ton roller. Although the rockfill was inferior to that assumed in design, it was decided to proceed with the construction using the same close-by quarry, thus accepting that the construction and post-construction deformations probably would be significantly larger than for the earlier asphalt concrete dams built in Norway. The asphalt core for the Storglomvatn Dam is 90 cm wide at the bottom decreasing to 50 cm, and the top 51 m has a constant width of 50 cm. The asphalt core for the Holmvatn Dam has a constant width of 50 cm. As the construction and post-construction deformations in the two dams were expected to be larger than in previous Norwegian asphalt core dams, and the dams are located in a region with some earthquake activity, the designers specified an asphalt mix with softer grade bitumen (B 180) and somewhat higher bitumen content (6.7% of total weight) than in the earlier dams.

The performance of the two dams has been monitored for twelve years since their completion in 1997 (Höeg et al. 2007[6]) and back-analyses of the dam deformations and asphalt core behaviour have been carried out (Wang 2008[7]). It is concluded that the behaviour is very satisfactory in spite of the large embankment deformations.

4 Asphalt core dams may be built on compressible foundations

The Eberlaste Dam in Austria represents a case where an embankment dam with an asphalt core was built on top of a deep compressible and inhomogeneous alluvium deposit. During construction the foundation settled about 2.20 m in the middle of the valley, and there were large differential settlements over short distances. In addition come secondary settlements after end of construction. No noticeable leakage has been recorded through the asphalt core in the Eberlaste Dam since construction of the dam 40 years ago. This must mean that the core has been able to adjust to the large differential settlements, tension stresses and shear strains without cracking or a noticeable increase in permeability. It is a demonstration of the material’s ductility and/or crack self-healing ability. The designers had the foresight to specify the use of an especially soft grade bitumen (B300) and a fairly high bitumen content in order to accommodate the anticipated large shear distortions.

Wang (2008[7]) and Hao and He (2008[17]) present the Yele asphalt core rockfill dam, China. The dam has a maximum height of 125 m and a crest length of 411m with a 300 m long extension over the right bank. The dam is located on an extremely complex foundation in a region of high seismicity. There is a quartz diorite rock base under an alluvial overburden of 35-60 m on the left bank, a 55-160 m overburden on the river bed, and more than 220 m of overburden on the right bank (Fig.1). The crest elevation is 2654.5 m and the dam is located in a very cold and rainy area.

For the difficult geological foundation conditions with an irregular and compressible overburden, and with the high regional seismicity, only an embankment type dam was considered feasible. Three alternatives were examined for the impervious barrier in a rockfill dam: (1) earth core (ECRD), (2) upstream concrete facing (CFRD), and (3) asphalt core (ACRD). To decide among these alternatives emphasis was placed on costs, severe weather conditions during construction, earthquake resistance, and compatibility with the geological conditions which might cause significant differential settlements across the valley. After all aspects had been considered, the ACRD alternative was decided to be the most suitable.

Due to the high seismicity at the site, the rockfill dam is designed with relatively gentle slopes 1V:2H upstream and 1V:2.2H downstream and a wide crest of 14 m. In addition, the top 30 m of the dam as well as the lower part of the upstream slope was reinforced by horizontal geo-grids.

An extensive field monitoring program has been implemented for Yele Dam, and the recorded results are back-analyzed and compared to those of other high rockfill dams with asphalt core. Based on the field measurements, the back-analyses, the tests on the properties of the asphalt concrete and the joint between the core and the plinth, it is concluded that the asphalt core of the Yele Dam performs very well. There are no indications of any leakage through the core or at the joint between the asphalt core and the concrete plinth above the foundation cut-off wall. However, as anticipated at this geologically very difficult site, there is some leakage under the dam in spite of the extensive use of deep cut-off walls and curtain grouting. In early 2008 the leakage amounted to about 260 l/s. Continuous surveillance is taking place to study and control the development of this under-seepage (Hao and He 2008[17]).

5 Relative merits of different embankment dam design alternatives

The relative merits of four embankment dam design alternatives are discussed below: dam with (1) earth core, (2) asphalt core, (3) concrete facing, and (4) geomembrane facing. In addition to estimated construction costs, other important factors determine which design alternative is preferred for a given site, e.g. safety aspects; weather conditions; total construction time (time until reservoir is full/useful); required construction expertise (contractor experience); potential dam overtopping during construction; maintenance costs; and environmental aspects affected by dam type and different construction activities. Foundation conditions will often govern the design. The safety and performance of a dam is inseparable from the capacity of its foundation.

5.1 Earth core

When suitable earth core material is available within a reasonable transportation distance, other designs can generally not compete with the earth core design in terms of economy. It may also be the most suitable type of design if the foundation is very compressible. An embankment with a wide earth core and wide filters is also a very good alternative to provide safe dam earthquake resistance, especially in cases where fault displacements may take place in the dam foundation.

However, if the available earth core material has a high clay content, and the dam is to be constructed in a region with heavy precipitation during long (or unpredictable) periods of the year, the construction schedule becomes uncertain and the core quality control may become difficult due to the inclement weather. The core material may be modified by material processing (e.g. mixing with other materials and/or drying) to make it more suitable for use, but then costs are added. The increased concern about interior erosion has led to very stringent filter design and construction criteria, and more processing of filter materials is required. This leads to increased costs. If the core is to be founded on fissured/fractured rock, it is mandatory to treat the rock surface with grout or concrete and properly placed protective filters to avoid erosion of core material into open cracks. This aspect has too often been overlooked, even in fairly recent dams. In the case of possible floods during construction, the earth core design is more vulnerable to damage by overtopping than for instance a dam with concrete facing or asphalt core. Scarps caused by earth core borrow areas are of more concern now than a few years ago and may, in some cases, become an important factor in the decision process.

5.2 Reinforced concrete facing vs. asphalt core

Past experience shows that one must be prepared for leakage through opened joints and tension cracks in the upstream concrete facing, especially in the vicinity of the perimeter joint and over the abutments. However, in a properly designed CFRD, with gradually coarser rockfill material from upstream to downstream, even a large leakage does not endanger the overall stability if the dam has been provided with ample downstream drainage capacity to safely accommodate the leakage flow. In many such cases a significant reduction in leakage through the facing has been achieved by merely dumping silt and fine sand (crack-stopper material) in the reservoir upstream of the leakage location. If the cracks are not too large, the silt then migrates into the crack and makes it much less pervious, especially if the sand–gravel zone under the concrete facing is made to function as a cohesionless filter arresting any further migration of the crack-stopper material.

However, recent experiences have shown the development of very large compression and shear cracks in some high CFRDs in narrow valleys (Pinto 2006[31]; Johannesson 2007[32,33]; Sabrinho et al. 2007[34]). These cases have now been analyzed to explain the unexpected behavior of the facing. It has to do with the vertical settlements and lateral displacements of the rockfill towards the center of a narrow valley and the resulting vertical and horizontal strains imposed on the concrete facing (e.g. Pinto 2009[35]). To avoid such cracking one requires high quality and extremely well compacted rockfill and special design considerations for the facing and the joints, designing compressible joints between the central slabs of the facing. Furthermore, the concrete facing should preferably not be placed until much of the post-construction creep deformations of the rockfill have taken place.

The asphalt core exhibits viscoelastic-plastic, ductile behaviour and has therefore the ability to relieve any stress concentrations and self-heal any tendencies to fissure or crack formation. There is no case of reported leakage through an asphalt core. It may be considered maintenance-free. An asphalt core can also tolerate foundation settlements and embankment deformations due to static and earthquake loading better than the inclined upstream concrete facing, and one can therefore accept the use of lower quality compacted earth- or rockfill (see Section 3). The asphalt core is protected from impact loads and damage by reservoir debris, deterioration due to weathering, and acts of sabotage (terror).

An experienced contractor is required to properly construct a concrete facing with attention to construction details, water stops and reinforcement at joints in the slab and along the important perimeter joint at the plinth. The construction of an asphalt core and the simultaneous placement of the transition zones on either side, is a much simpler and controllable operation than the corresponding construction of the concrete facing. Furthermore, the hazard the workers on the steep upstream CFRD slope (usually 1.3H:1V) is exposed to, is much higher than that experienced in asphalt core construction.

The plinth for the asphalt core is shorter than for the CFRD and is much simpler in design and construction. The required width of the plinth to reduce the hydraulic gradient to safe levels, is determined as for the CFRD plinth. The foundation grout curtain under the plinth for an asphalt core dam is therefore also shorter than for a CFRD. On the other hand, a significant advantage of the CFRD design is that the plinth construction and the grouting under the plinth may take place almost independently of the construction of the other zones of the embankment. The construction of the asphalt core and the adjacent transition zones cannot start until the plinth and grouting are completed under the deepest section of the dam.

The concrete facing of the CFRD provides slope protection against wave action, while the core dam requires rip-rap protection. Furthermore, the rockfill under the CFRD facing has the advantage of being dry (or only partly saturated) under static and earthquake loading conditions and can therefore have a steeper upstream slope than core dams. The asphalt core dam may have a steeper slope than a dam with a wide or sloping earth core. However, if the embankment is to rest on a weak foundation, the external dam slopes for all three alternatives may be governed by the foundation strength and stability.

The crown portion of a core dam is usually significantly more robust than that for the CFRD which, for economy, relies on the use of steep dam slopes and a concrete parapet wall that may be vulnerable, for instance during earthquake loading.

The asphalt core allows reservoir storage during construction such that the reservoir may be full by the end of embankment construction. The CFRD cannot provide storage during construction unless the facing is built in sections (and not only after the embankment is completed). Some of the more recent CFRDs have been built in sections (stages) to shorten the construction period. This requires special attention to rockfill deformations and their effects on the facing and joints as some areas of the facing are already in place while the embankment rockfill is being raised above that level and in some cases also adjacent to the already constructed concrete panels. After the experiences with high CFRDs in narrow valleys (e.g. Pinto 2009[35]), one may return to the practice of constructing the facing after the embankment is completed. However, this will lengthen the total construction period.

5.3 Geomembrane facing

The flexible geomembrane used as upstream facing provides many of the same advantages as the concrete facing but avoids some of the disadvantages due to membrane flexibility and ability to accommodate the rockfill deformations during and after construction and earthquake loading. The membrane may, for instance, be placed directly on extruded concrete curbs as used for modern CFRDs.

The quality and toughness of geomembranes are steadily improving, as well as the methods of installation, but remaining concerns in the profession are their vulnerability to impacts, ice loads (tearing), acts of terror, and the effects of aging and weathering. To alleviate some of these concerns the membrane may be fully or partly covered by a protective layer, but if that is deemed necessary, it increases costs and reduces the relative competitiveness. However, the geomembrane alternative will undoubtedly replace the use of stiff reinforced concrete facings in many future dams.

6 Conclusions

We now have 50 years of successful experience with the performance of asphalt core embankment dams. Among all the dams that have been built, there is no case of reported leakage through the asphalt core.

Recent research and field studies have documented that (1) asphalt concrete is very resistant to earthquake loading and can tolerate high tensile and shear strains without cracking, even at low temperatures; that (2) the strict requirements to aggregate quality used in pavement design may be relaxed, and locally available aggregates may be used; that (3) the asphalt core may be raised at a higher construction rate than that practiced for earlier asphalt core dams without compromising core quality, and that (4) several grades of bitumen exist, and admixtures may be used to further improve the geo-mechanical properties of the asphalt concrete mix if required to satisfy special design requirements.

Case studies have demonstrated that asphalt core dams may be successfully constructed with much lower quality rockfill than that used in previous dams of this type. Asphalt core dams have also been built where rockfill is not available and other materials have been used.

Most existing asphalt core dams rest on rock foundations, but there are other cases where asphalt core dams have been built on deep and compressible alluvial deposits.

Comparative studies in several recent projects have shown the asphalt concrete core embankment dam to be a very competitive design alternative both with respect to safety and economy. Presently there are more dams of this type under design and construction than ever before.

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