Embankment dams under dynamic heavy traffic loading: Challenges and perspective

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GeoCalgary 2022 October 2-5
Reflection on Resources

ABSTRACT
Heavy traffic on embankment dams is commonly discouraged because structural integrity damage could occur and potentially modify its behavior. However, special transport needs often occur in isolated areas, either for mining purposes or transporting heavy equipment, and permitting heavy vehicle traffic over dams can be strategic economically and environmentally. Since vehicle damage is not a conventional dam design criterion, traffic permissibility determination and damage quantification is a non-trivial problem which must be analyzed accordingly. This article presents theoretical bases to guide the analysis of heavy vehicles' effect on embankment dams. Proper damage quantification and establishment of an acceptability criterion for heavy vehicles' effect on dams is a work in progress that will maximize usefulness of available infrastructure, especially in remote areas with limited road infrastructure.

RÉSUMÉ
La circulation de véhicules lourds sur les barrages en remblai est généralement déconseillée en raison des dommages qu'elle peut causer à l'intégrité de la structure. Cependant, dans les zones isolées ayant des besoins particuliers en matière de transport, que ce soit pour l'exploitation minière ou pour le transport d'équipements lourds, autoriser la circulation de véhicules lourds sur les barrages peut être bénéfique sur le plan économique et environnemental. Comme les dommages causés par les véhicules ne sont pas un critère conventionnel dans la conception des barrages, la détermination de l'admissibilité du trafic et la quantification des dommages qu'il génère est un problème non trivial, qui doit être analysé en conséquence. Cet article vise à présenter des bases théoriques pour guider l'analyse de l'effet des véhicules lourds sur les barrages en remblai. La quantification adéquate des dommages et l'établissement d'un critère d'acceptabilité de l'effet des véhicules lourds sur les barrages est un travail en cours qui permettra de maximiser l'utilité de l'infrastructure disponible, en particulier dans les régions éloignées où l'infrastructure routière est limitée.

1 INTRODUCTION

The use of dam crests as infrastructure for heavy vehicle traffic is usually not recommended. Still, it can significantly reduce travel times and costs, resulting in economic and environmental benefits (i.e., reduced fuel consumption, avoided bridge construction). However, there is concern about the impact of heavy vehicles on the performance and safety of embankment dams. These major infrastructures are not designed to consider repeated vehicular traffic as a condition or parameter of analysis and, more specifically, damage accumulation mechanisms induced by heavy vehicles.

Analysis under dynamic loading is common practice when studying seismic events in dams; however, using this type of analysis for dynamic loads such as those transmitted by heavy vehicular traffic presents some variations and conditions. For seismic events, displacements originate from a dam's foundation, while repeated loads are applied to a dam's crest in the case of heavy vehicle traffic. In both cases (dynamic earthquake loading and dynamic vehicle loading), repeated loads have a cumulative damage effect, which can lead to structural failure in certain circumstances or generate conditions that can compromise the mechanical properties of embankment soils or the hydraulic capacity of the dam.

The paper aims to introduce various considerations for analyzing the dynamics of dams under heavy vehicle loads. It uses the dam crest settlement analysis as a reference.

2 EARTH AND ROCKFILL DAMS

Dams are obstacles to a river's natural flow and are built for different purposes, including water storage for drinking water supply and hydroelectricity.

Embankment dams are earth and/or rockfill structures that resist water pressure induces by a reservoir due to their own weight. They are constructed of an inherently impermeable material or have an impermeable core. Figure 1 shows a typical cross-section of a zoned dam with an impermeable core. This type of dam is divided into several zones with different properties and serving different functions (Fell et al., 2005): Zone 1 provides impermeability and part of the stability, using fine, silty and clayey soils. Zone 2 is composed of soils with a permeability of two or more orders of magnitude greater than that of zone 1. This zone functions as a protective filter for zone 1 and contributes to dam stability; it is also a transition element between zone 1 and zone 3. Zone 3 is composed of coarse materials, such as gravel or crushed rock, with high internal friction. The auxiliary rock fill, called Zone 4, protects other zones against wave and ice erosion. Of the zones described above, Zone 1 (core) allows the dam to retain water, while other zones provide core stability and protection.

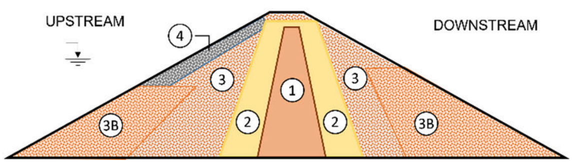


Figure 1. Typical cross-section of an embankment dam with an impervious core.

Dam design considers several factors related to topography and site geology, hydrological characteristics of watersheds, river regime, mechanical properties of foundation soils or rock, nearby available construction materials and climate. Embankment dam stability depends on material shear strength and the cross section in which the materials are arranged (Fell et al., 2005). Similarly, other aspects can also influence stability, such as construction methods, proper operations, monitoring and maintenance of the dam.

Earth and rockfill dams must withstand loading conditions that arise during construction and subsequent operation. Acting loads include self-weight, reservoir water level variation, pore-water pressure seepage flow pressures, and finally earthquake-driven loads.

2.1 Dam crest settlement

In dams, performance parameters define the analysis, which are key indicators used to monitor and predict dam and foundation response to the full range of loads for critical conditions in a project (USACE, 2004). Permanent deformation is one of the performance parameters that is common to earthquakes and heavy vehicle loads on dams. Deformation induced in the dam crest is also known as crest settlement.

Dam crest settlement can be used as a general indicator of other damage mechanisms, such as instability phenomena, internal erosion, and liquefaction-induced effects affecting embankment or foundation soils.(Costigliola et al., 2022).

Methods for estimating crest settlement in dams under dynamic/seismic loading are described in the literature in three main categories. (1) numerical modelling methods, (2) simplified Newmark-based methods, and (3) empirical methods. A brief explanation of each method will be given below.

In numerical modelling-based analysis, finite element and finite difference-based methods are most commonly used approaches (Ventrella et al., 2019). These have the capability to analyze various aspects of dynamic responses of a dam's body; for example, slope stability, liquefaction, vertical and horizontal displacement, cracking, and dam-reservoir interaction. Additionally, they can include complex geometries effects in 2D or 3D analysis.

In engineering practice, numerical analyses of dams are carried out through commercial software. One of the limitations of numerical modelling is the need for an advanced constitutive model to capture the nonlinear seismic behavior of a dam, which increases the complexity of numerical simulation models.

Simplified analysis methods are generally based on Newmark's theory, which assumes that the shear of a sliding mass on the failure surface of a predefined slope is analogous to the deformation mechanisms of the dam (Newmark, 1965). Newmark considered the sliding mass as an undeformable block resting on an inclined plane. The method calculates the permanent displacement induced by an accelerogram (a(t)) acting at the base of the slope by double integration of the acceleration amplitude $a_r(t)$ exceeding a critical acceleration threshold, a_c, as indicated in Equation 1.

$$a_r(t) = a(t) - a_c \qquad [1]$$

Therefore, the total amount of permanent displacement is determined by the number and intensity of acceleration peaks above a threshold (a_c), known as critical acceleration.

Crest settlement can be roughly estimated as a combination of permanent deformation of downstream and upstream landslide slopes (Gazetas & Dakoulas, 1992). However, evidence-based research has shown that settlement mechanisms of a dam crest are different from that assumed by Newmark (Swaisgood, 2003), so applying this principle should be reconsidered.

Established empirical methods for dam deformation predictions are based on behavioral analysis of information from different dams during previous earthquakes. Swaisgood (2003) proposed relative crest settlement as an index of earthquake damage to dams, using Equation 2 for its calculation.

$$S = \frac{\Delta}{DH + AT} \qquad [2]$$

Where Δ is dam crest settlement (in meters), D.H. is dam height (in meters), and AT alluvial depth (in meters), as shown in Figure 2.

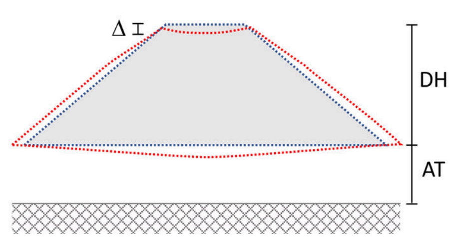


Figure 2. Mechanism of seismic deformation in earth dams, crest settlement.

Swaisgood (2003) proposes an equation that correlates the relative settlement of dam with seismic magnitude (M_w)

and with foundation peak ground acceleration (PGA). This empirical model is described in Equation [3].

$$S = e^{(6.07 \times PGA + 0.57 \times M_w - 8)} \quad [3]$$

Where S is the amount of settlement of dam crest (in %), PGA is the peak horizontal ground acceleration of the foundation rock (in g) recorded or estimated at the dam site, and M_w is earthquake magnitude (in surface wave scale: $M_{S.}$).

The Swaisgood equation is based on an extensive database of historical case. It was found that the statistical fit of the calculated values was similar to that of the data from the various well-documented earthquakes. It has the limitation of generalizing under the same approach the expected settlement in different types of dams (i.e. earthfill, earth core rockfill dam, concrete faced rockfill dam, etc.). Likewise, in some cases in the database, the value of PGA is estimated and not measured on-site, which may increase the uncertainty of the model.

The statistical similarities between the calculated settlement values and the actual settlement values suggest that the prediction of crest settlements is not improved unless the ground accelerations are improved.

Empirical methods, such as Equation 3, are more cost-effective, less complicated and require less time for their application. However, their predictive capability may be limited and are conditioned by the database used for their formulation.

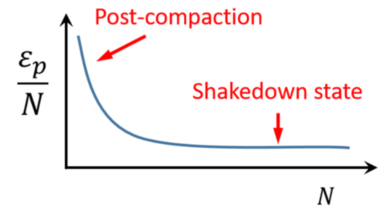
In the case of permanent deformation settlements induced by dynamic vehicle loads, Pérez-González et al. (2020) proposed a method to predict permanent deformation in earth and rockfill dams' core. This analytical method, relies on field data to develop their proposal, but also on numerical simulation and laboratory tests. The following section gives a summary of this method.

2.2 Permanent deformation in dam cores caused by heavy vehicles

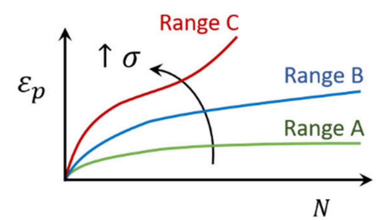
Dynamic conditions established by heavy vehicular traffic is characterized by magnitude and number of load repetitions applied. A material subjected to cyclic loading usually shows a behavior associated with stress states to which it is subjected, and this behavior may change as the number of cycles increases. With a high number of load cycles, permanent deformation in materials may reach a state of equilibrium, where strain rate (permanent deformation caused by a single load cycle) tends to stay at a relatively constant value, as shown in Figure 3a.

Figure 3b shows illustratively evolution of permanent deformation under repeated loading. This behaviour has been previously explained using Shakedown theory(Aleksandrov et al., 2018; Werkmeister et al., 2001), which relates deformation magnitude to stress levels acting on a material. In this approach, three categories of material response, or stages, under repeated loading can be identified (Werkmeister et al., 2005):

- Plastic shakedown, characterized by a plastic response for a finite number of load repetitions, and after completing the post-compaction period, responses become fully resilient. It is labeled as "range A."
- Plastic creep, where the material exhibits mostly stable, long-term permanent strain rate and buildup. It is labeled as "range B."
- Incremental collapse is characterized by a continuous increase in permanent deformations with each loading cycle, with failure occurring relatively quickly. It is labeled as "range C."



(a)



(b)

Figure 3. Permanent deformation behavior of materials subjected to cyclic loading. (a) deformation rate, (b) Shakedown states.

Estimation of permanent deformation is associated with vertical plastic deformation and layer thickness (ARA Inc, 2004; Doré & Zubeck, 2009), and in a multilayer system is generally defined by Equation 4.

$$\delta = \sum_{i=1}^{n} \varepsilon_p^i \times h^i \quad [4]$$

Where δ is total deformation in the structure, n the number of layers, ε_p^i and h_i are the permanent vertical strain in the middle of layer i and its thickness, respectively. Starting from Equation 4, Equation 5 can be derived for a core's permanent deformation calculation of an embankment dam using the strain rate (Pérez-González et al., 2020).

$$\delta = \frac{\dot{\varepsilon}_p}{2} \times N \times \widetilde{D} \quad [5]$$

Where, $\dot{\varepsilon}_p$ is permanent strain rate, associated with stress state, N is the number of load repetitions and $\widetilde{D}$ is load influence depth. Value of $\widetilde{D}$ is a distance in millimeters (mm) measured from the core's top (i.e., at the top of the core, $\widetilde{D}$ = 0 mm), and represents depth to which stresses will contribute significantly to permanent deformation accumulation, and is conditioned by stress states.

The approach Pérez-González et al. (2019, 2020) use shakedown theory to simultaneously determine permanent deformation and limit state of a dam's core under dynamic vehicle loads. A general equation for permanent strain rate as a function of stress states is used, as described in Equation 6.

$$\dot{\varepsilon}_p = C_r \times e^{\alpha\left(\frac{q}{p}\right)^2+\beta\left(\frac{q}{p}\right)+\gamma} \quad [6]$$

Where C_r, α, β and γ are adjustment factors, and q/p is the ratio between deviatoric stress (q) and mean stress (p), defined by the following equations:

$$q = \sigma_1{}' - \sigma_3{}' \quad [7]$$

$$p = \frac{\sigma_1{}' + 2 \times \sigma_3{}'}{3} \quad [8]$$

Where σ_1' and σ_3' are major and minor effective principal stresses, respectively.

3 DISCUSSION

The effect of dynamic earthquake loads on dams has been extensively explored in the literature. Its consideration is a fundamental part of performance parameters that characterize a dam. On the other hand, influence of dynamic vehicular loads on earth dams has been explored in recent research.

Both conditions contribute directly to dam crest settlement , so cumulative effect of permanent deformation associated with dynamic loading of vehicular traffic should not be ignored a priori during dam analysis. In the following sections, two major challenges for analyses of heavy vehicles' effect on dams will be presented, and the authors' perspective will be given.

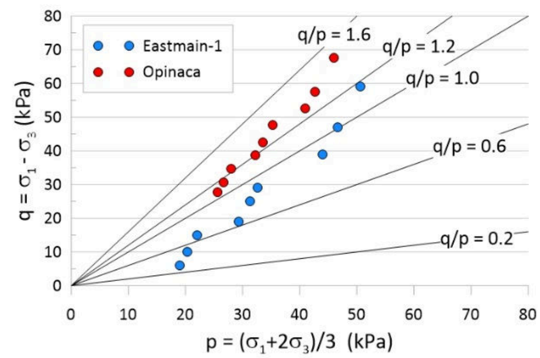
3.1 Limit or critical state

Like the critical acceleration (a_c) principle, used in the Newmark criterion, it is necessary to define a reference parameter when studying permanent deformations in a context of heavy vehicular loads on a dam. Its definition should result from influence analysis of this deformation accumulation on a dam's performance.

As proposed by Pérez-González et al. (2020), Shakedown theory can be beneficial to define a reference value. However, current criteria for granular materials under the Shakedown theory are directly applicable to pavement materials, which operate under different stress states than those expected in large embankment dams. However, new limits can be proposed and evaluated to agree on unified criteria for dam analysis.

Figure 4 shows results of dynamic triaxial tests on samples from two dam cores. In the trend defined by these results, using the strain rate in the material's equilibrium phase as a reference, a stable zone with little variation in the strain rate in relation to stress state increase (q/p value) is discernible. In addition to this stable zone, there is another zone where permanent strain rate increases rapidly as stress state increases. It is this type of behavior that can be modelled using Equation 6.

Figure 4a shows stress paths applied in laboratory, and Figure 4b shows strain rates as a function of stress state q/p. In both cases, it can be noted that a strain rate of 4×10^{-3} με/cycle represents a reasonable limit between a stable behavior and a more accelerated deformation (higher strain rate). For example, in the Eastmain-1 dam core a q/p value higher than 0.80, and in the case of the Opinaca core a q/p value higher than 1.2, will generate permanent deformation. This deformation rate could be used as a reference as a boundary condition for the relevant development of permanent deformation due to heavy vehicles. More research on this aspect should be carried out.



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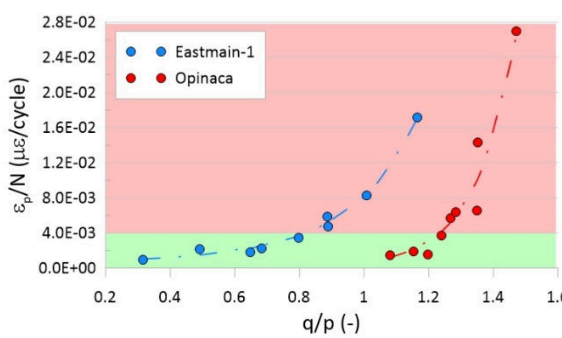


(b)

Figure 4. Dynamic triaxial results in dam cores (a) stress path, and (b) permanent deformation rate as a function of q/p.

3.2 Maximum allowable deformation

Another challenge that should be studied, in the case of subjecting dams to heavy vehicle loads, is the maximum allowable deformation. Definition of this value is a challenge, since the useful life of dams is very long. During this period, many variables can affect criteria that can be used to admit or not a dam crest or dam core deformation.

Considering dam settlement caused by dynamic loads, as described in Equation 2, can be made up of two components (seismic loads and vehicular loads), Equation 9 can be used to describe this phenomenon.

$$\Delta = \delta_{EQ} + \delta_{HV} \quad [9]$$

Where $\delta_{E.Q.}$ and $\delta_{H.V.}$ represent the deformation caused by earthquakes and heavy vehicles respectively. Using an empirical model, as described in Equation 3, maximum allowable deformation in heavy vehicles' cases can be derived as follows:

$$\delta_{HV} = \left(S_{adm} - S_{EQ}\right) \times \left(DH + AT\right) \quad [10]$$

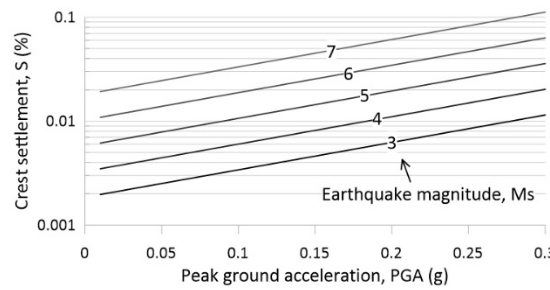
In Equation 10, S_{adm} is the allowable settlement (in %), and S_{EQ} is the settlement caused by earthquakes (in %). This percentage is referred to the sum of dam height and alluvial depth (DH+AT), as shown in Figure 2.

Definition of an allowable settlement is still a value to be reviewed. There is a notable difference in areas affected by dynamic loads application. For example, the $\widetilde{D}$ determined by Pérez-González et al. (2020) shows that influence of dynamic loads from heavy vehicles will be limited in depth (as expected), as opposed to an earthquake, which will affect the full thickness of a dam and its alluvial foundation (DH+AT). Table 1 provides an identified threshold for earthquake-induced damage to dams based on comprehensive case reviews (Swaisgood, 2003; USCOLD, 2000).

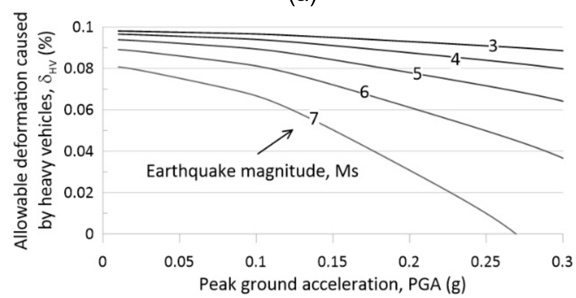
Table 1. Earthquake-induced damage levels in embankment dams and their performance index (Aliberti et al., 2019).

Levels of damage	Limit states	Performance indexes
None	Operational limit state	S < 0.1 %
Minor	Damage limit state	S < 0.4 %
Moderate	Life safety limit state	S < 1.0 %
Serious	Collapse limit state	S < 2.5 %

Using as reference values presented in Table 1, and considering that total settlement due to dynamic loading will result from earthquakes and heavy vehicle loads (see equation 9), allowable value for settlement caused by heavy vehicles can be estimated to guarantee that in a probable seismic event, a dam will remain within operational limit states. Assuming an allowable settlement limit (S_{adm}) of 0.1% at the dam crest, Figure 5 shows the allowable settlement caused by heavy vehicles when combined with different seismic events.



(a)



(b)

Figure 5. Dam crest settlement (a) settlement prediction using Equation 3, (b) allowable deformation for heavy vehicles, determined with Equation 10.

A criterion such as the one described in Figure 5b can serve as a reference for decision making in impact analyses of heavy vehicles traffic. This simplified tool, offers decision making thresholds on deformation admissibility that can be attributed to heavy vehicles followed by additional seismic events for given PGA and M_w values.

On the other hand, given problem variability due to changes in magnitude, configuration, and speed of dynamic loads generated by vehicular traffic, a design/analysis approach, based on load and resistance factors, may be an interesting alternative.

Load and resistance design factors (LRDF) is a method in which design loads are increased and design resistance is decreased with factors that consider system uncertainties (Fenton & Griffiths, 2008). This approach is based on limit state criterion. It divides limit state in two categories: (1) strength limit state, associated with maximum strength's behavior, and (2) serviceability limit state, associated with structure functionality. A general expression for permanent deformation analysis in dams using LRDF can be formulated as shown in Equation 11.

$$\sum \gamma_i \times \delta_i \leq \varphi \times \delta_n \quad [11]$$

Where γ_i is the load factor, generally greater than 1, δ_i is the estimated permanent deformation (in mm), φ is the resistance factor, generally smaller than 1, and δ_n is the allowable permanent deformation or dam crest settlement (in mm).

The subscript *i* can be associated with various conditions that will contribute to deformation or settlement in dam crest, such as earthquakes ($\gamma_{E.Q.}$, $\delta_{E.Q.}$) or action of heavy vehicles ($\gamma_{H.V.}$, $\delta_{H.V.}$). Other aspects not related to dynamic loading, such as elastic settlement, primary and secondary consolidation settlement, can also be included in this analysis. Some methods for dam crest deformation determination (δ_i), for dynamic earthquake and vehicle loading, have been presented previously. Definition of δ_n still needs to be discussed, mainly to develop a rational criterion for it. Likewise, the factors of γ_i and φ must be calibrated to the probabilistic characteristics associated with occurrence of critical events during a dam's lifetime.

4 CONCLUSIONS

The main effects of excessive deformations in embankment dam crests are loss of freeboard, damage to adjacent structures within or above the dam, slope cracking (most detrimental to the impermeable core), development of localized weak zones susceptible to hydraulic fracturing or internal erosion, and instrumentation failure.

A criterion for determining heavy vehicles' influence on a dam, and their magnitude, is yet to be defined. Use of deformation rates seems a promising benchmark, however, more research is needed to define an acceptability limit in terms of damage potentially affecting a dam's performance.

Dynamic loads generated by heavy vehicles contribute directly to dam crest deformation, their influence must be added to deformations resulting from earthquakes to obtain an adequate estimate of a dam's behavior. This approach can be applied by means of empirical methods, such as the one used in this paper, or other, more advanced approaches, such as numerical modelling.

In this paper, some general aspects of response analysis of embankment dams to dynamic loads were compiled. Thus, effects of heavy vehicles can be combined with that of seismic events in dam crest settlement studies. Heavy vehicles' effect on dams is a topic partly studied, and authors have provided an overview of how it can be addressed. However, more research is needed to cover necessary aspects to perform a formal dam analysis and to define admissibility criterion of heavy vehicle traffic on embankment dams.

5 ACKNOWLEDGMENT

The authors would like to acknowledge Hydro-Quebec and NSERC for their interest in and support to this research.

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