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Influence of clogging rate of toe drainage blanket on the response of homogeneous earthen dam resting on impervious foundation bed

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Arindam Dey & Priyanka Talukdar
Department of Civil Engineering, Indian Institute of Technology Guwahati, India, arindamdey16@gmail.com

ABSTRACT: Dam failures has always sought attention of the researchers and engineers, owing to its cataclysmic impact upon the living and the environment. Poor drainage conditions generated due to clogging leads to be significant variation of the pore water pressures within the earthen dam, thereby leading to noticeable temporal changes in the phreatic level with the body of the dam and can even achieve the highest levels in the downstream face. This scenario seriously influences the safety of the dams. Thus, clogging is a major concern limiting the lifetime of the structures and it becomes essential to understand its effect on earthen dams. Furthermore, the clogging rate is supposedly the governing factor for the performance life of an earthen dam. In this regard, an attempt is made to understand the influence of the rate of clogging on the response of homogeneous earthen dam comprising drainage blankets. Three different clogging rates as 1 m/day, 0.1 m/day and 0.01 m/day are simulated. Finite element analyses are carried out for both steady state and reservoir operational conditions that included the drawdown and rise-up scenarios. For different reservoir conditions, the influence of clogging rate is observed to be different. It is observed that the generation of excess pore-water pressure increases as the clogging rate decreases for the steady state and rise-up condition, while it decreases with a decrease in the clogging rate for the drawdown condition.

KEYWORDS: Clogging rate, Homogeneous earthen dam, Drainage blankets, Finite Element Analysis, Reservoir conditions

1 INTRODUCTION

Earthen dams are always associated with the seepage of water that is impounded in the upstream reservoir, and which constantly attempt to traverse the path of least resistance through the body and foundation of the dam. To protect these dams, appropriate internal filtering and drainage blankets are used. However, the temporal or spatial reduction in the permeability of these filters and drainage blankets becomes a very critical issue. Along the life of a dam, drains and drainage blankets can get gradually clogged, and lose their designed capacities to facilitate the seepage flow and control the uplift pressures. Particulate clogging in porous media is of substantial importance in geotechnical engineering (Reddi et al., 2000). Several studies in recent decades reported dam failures due to inadequate filter design (Vaughan & Soares 1982, von Thun 1985, Peck 1990).

The occurrence of clogging can be detected from the instrumentation readings, which is often indicated by a decrease of flow in the drains and an increase in the exit pressures in the foundations of the dam. There are many causes of drain clogging, and the most common ones include the calcium carbonate deposits from the dam concrete, the grout curtain, the foundation rock (Ruggeri 2004) or bacterial deposits (Rutenback & Day 1999). The other causes are attributed to accumulation of materials from the drain walls, or that carried by seepage into the drains, or a combination of both (Koerner & Koerner 1991, Cedergren 1994). Researchers have discussed the most common forms of drainage clogging and its influence on seepage through foundation for concrete dams built on permeable rock foundations (Silva 2015). Studies have been carried out to understand the influence of toe drain clogging on the response of the earthen dams (Talukdar & Dey 2017). The effect of clay blanket and cut-off wall with sand filter on the seepage characteristics have been studied (Ullah et al., 2019). Attempt has been made to understand the filter clogging mechanism by monitoring the flow rate and sensor pressure (Omer et al., 2013). The effect of drain size during steady and transient reservoir condition on the response of the dam has been studied (Malekpour et al., 2012). The effect of suspended particle size on the clogging of soil filters have also been investigated (Banihashem & Karrabi 2020). Clogging of drains can possibly lead to a reduction of drain diameter, a reduction of drainage length or a reduction in the drainage capacity to carry the discharge. Once clogged, partially or fully, the filters and drainage blankets within an earthen dam would no longer serve its purpose, and may generate a situation of impending dam failure. Therefore, it becomes important to understand the impact of clogging of the toe drainage blankets on the earthen dams.

The clogging rate of toe drainage blanket is one such aspect that needs to be explored. Very few studies has been conducted in this regard until date. Studies have been made to investigate the impact of clogging rate on MSW landfill systems (Flemming & Rowe 2004, Rowe et al., 2011). Field investigations have been carried out to find out the effect of clogging on drainage systems where amount of clog accumulated has been monitored from time to time (Wersocki 2014). Investigating the rate of clogging and understanding its impact on the earthen dams can be very crucial in protecting the structure. Thus, in this study, an attempt has been made to investigate the influence of clogging rate of toe drainage blanket on the response of homogeneous earthen dams. The analyses are carried out for both the steady-state and transient reservoir conditions using finite element (FE) analysis. For this purpose, seepage analyses and coupled stress-deformation analyses are carried out, using the Seep/W and Sigma/W modules of Geostudio 2012 respectively.

2 SCHEMATIC MODEL OF HOMOGENEOUS EARTHEN DAM

A FE model has been used to understand the effect of clogging rate of the drainage blanket on the earthen dam. The cross-section of the homogeneous earthen dam model, along with its relevant dimensions, is shown in Figure 1. The height of the earthen dam is 10 m and its width is selected as 50 m. The upstream and downstream slopes has inclinations of 2.5H:1V and 2.2H:1V, respectively. A crest width of 3 m and a free board of 1 m is maintained for the chosen dam section. The height and width of the foundation are considered 10 m and 80 m respectively. The relevant dimensions for the dam section has been chosen as per IS 12169 (1987).

The length of the horizontal toe blanket is considered 10 m and its width is 1 m (as per IS 12169: 1987). The entire drainage blanket of 10 m length has been divided into five different sections, each having a length of 2 m. The effect of clogging is simulated by reducing the material permeability of the drain sequentially where the clogging starts from the outermost section (near the toe) as shown in Figure 2.

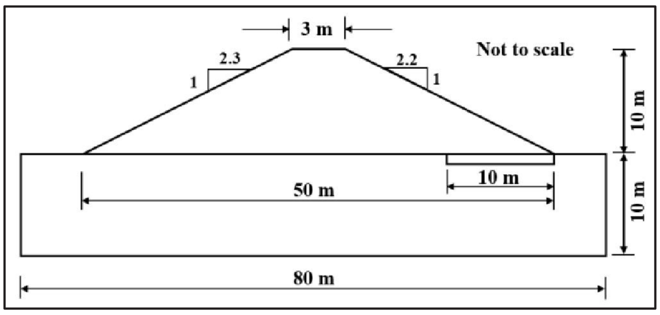


Figure 1. Schematic cross-section of the homogeneous earthen dam model with horizontal toe drainage blanket.

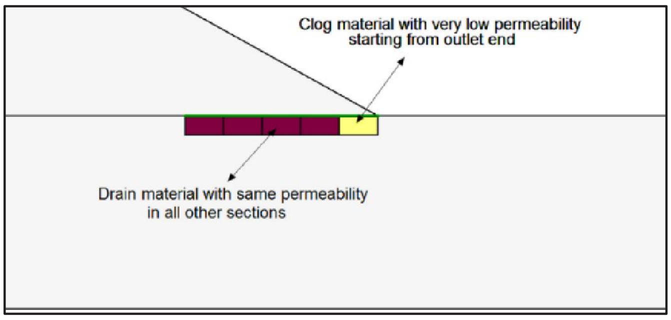


Figure 2. Representation of the clogging mechanism initiating from the outlet end of horizontal toe drainage blanket

2.1 *Material Properties*

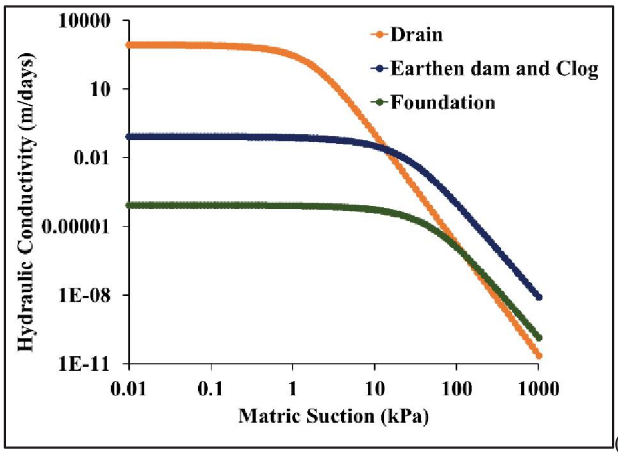
The simulation of the models, comprising different soil characteristics, requires proper assignment of the material models and input parameters. For the seepage analyses, the earthen dam is represented by 'saturated/ unsaturated' material model, while the foundation is catered by 'saturated only' material model. For the coupled stress-deformation analyses, the material of earthen dam is represented by 'elastic-plastic' material model, supported by the category 'effective parameters with pore-water pressure change (effective parameters w/PWP change)'. For the same analyses, Figure 3 shows the estimated hydraulic conductivity and volumetric water content functions for the materials in earthen dam, foundation, drainage blanket and the clog material.

Based on literature survey (IS 12196: 1987, USBR 1987, USBR 2014, Seep/W 2012), coupled with engineering judgment, the soil properties to be used in the present modeling are decided. The strength and stiffness properties of various materials used in the numerical simulation is listed in Table 1.

It is observed from Figure 3, as well as from Table 1, that the properties for the earthen dam material and clog material are the same, as it is considered that finer materials in the earthen dam will migrate and lead to the clogging of the drains. During the clogging process, the materials with which the drain would be clogged cannot have a permeability lower than that of the earthen dam material.

2.2 *Meshing and Boundary Conditions*

A proper discretization or meshing is immensely important for the accuracy of the results obtained from finite element simulations. In the present study, an unstructured mesh (comprising combined quad-and-triangular elements) is used to discretize the domain. A total of 1636 nodes and 1531 elements, with an average element size of 1m, is used as mesh in the geometrical boundary, as shown in Fig. 4.



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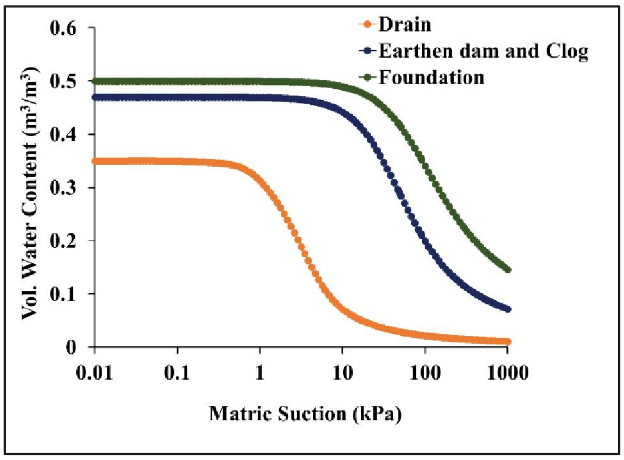


(b)

Figure 3. Properties of various material as used for Sigma/W analyses (a) Hydraulic conductivity function (b) Volumetric water content function

Table 1. Material properties of various components of clogged earthen dam

Material	c (kPa)	φ (degree)	γ (kN/m^3)	$E_{modulus}$ (MPa)	k (m/s)
Earthen dam	10	25	20	15	10^{-7}
Impervious Foundation	15	20	20	30	10^{-10}
Drainage blanket	2	30	18	12	10^{-2}
Clog	10	25	20	15	10^{-7}

*c – Cohesion, φ – Angle of internal friction, γ – Unit weight, $E_{modulus}$ – Elastic modulus, and k – Saturated hydraulic conductivity

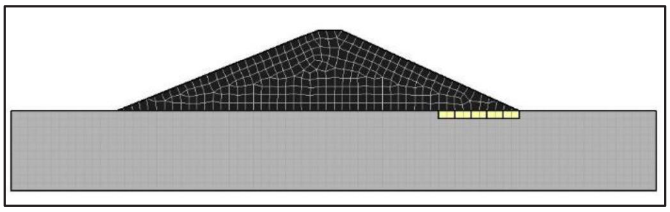
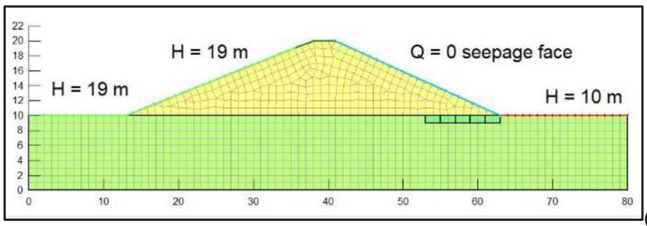


Figure 4. A typical meshing of the homogeneous earthen dam

The boundary conditions are important considerations in any finite element analysis. In a steady-state analysis, the hydrostatic water pressures and flow rates are invariant of time. Thus, for this case, all the boundary conditions comprise either constant heads (or pressure) or constant flux values. However, in a transient analysis, the pressure conditions changes with time. Accordingly, the boundary conditions to be adopted either are functions of time or considered as a response to flow volumes exiting or entering the flow regime. In the present study, for a steady-state analysis, a constant total head boundary condition, a potential seepage face boundary condition and a stress/strain boundary condition along the upstream and downstream face and the base of the earthen dam are utilized. In the case of transient analysis, the total head and reservoir elevation is considered as a function of time along the upstream face of the dam. Figure 5 shows a typical schematic of the boundary condition adopted in the present study.



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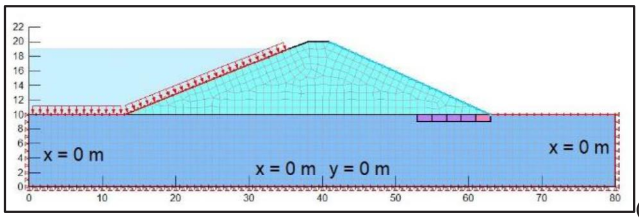


(b)

Figure 5. Boundary conditions used in the analysis (a) Seep/W (b) Sigma/w

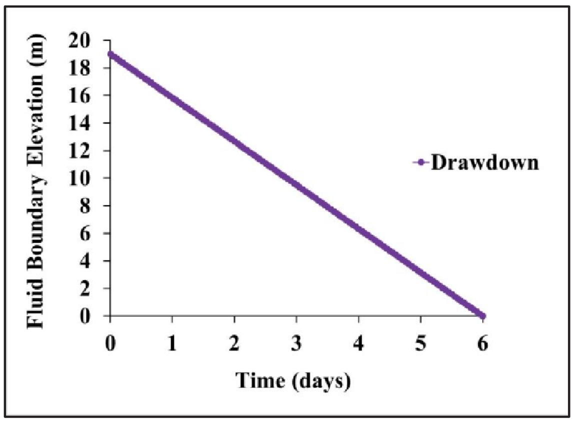
2.3 *Analysis Methodology*

In the present study, the primary objective is to investigate the influence of clogging rate of the toe drainage blanket on the response of homogeneous earthen dam at its steady state and reservoir operational conditions. In this regard, the FE models were initially analyzed in Seep/W module by subjecting them to 'initial steady-state seepage analysis' to establish the in-situ pore-water pressures and total head conditions under steady-state conditions The initial stress conditions were generated using the 'in-situ analysis' of Sigma/W module. The scenarios with different clogging rates are modeled using the 'Coupled Stress/PWP analysis' in Sigma/W module, in which earlier estimated pore-water pressure (from steady-state analysis) and initial stresses (from in-situ analysis) are used to define the initial conditions for the transient state.

The clogging rates are calculated by estimating the number of days required to clog the entire drain length. Accordingly, the toe drainage (10 m long) is considered to be clogged within 10 days, 100 days and 1000 days, thereby resulting in three different clogging rates as 1 m/day (high rate of clogging), 0.1 m/day (moderate rate of clogging) and 0.01 m/day (high rate of clogging), respectively. The adopted high rate of clogging is hypothetical and is considered only for the sake of understanding the behavioral differences in the response of the dam in comparison to other practical and reasonable rates. The distribution of pore-water pressure is noted for the 3rd stage of clogging i.e., for the 6th day, 60th day (1 month) and 600th day (1.64 years), corresponding to the high, moderate and low clogging rates, respectively. The influence of the clogging rates on the response is studied for both the steady state and transient analyses. For the transient analysis, the rate of reservoir rise-up and drawdown are considered 1.5 m/day, as shown in Figure 6.

3 RESULTS AND DISCUSSIONS

Figure 7 highlights the influence of clogging rate on the pore-water pressure (PWP) distribution for both the steady-state and transient reservoir conditions. The PWP distribution is exhibited all along the base of the dam. Figure 7(a) reveals that under the steady-state reservoir condition, the PWP is marginally higher for the lowest clogging rate. In case of a lower clogging rate, the saturation front gets a larger time to migrate through the body of earthen dam towards its downstream, thereby leading to a dissipation and reduction in PWP. Figure 8 manifests the distribution of pore-water pressure in the entire section of dam and foundation under the influence of varying clogging rates. For a higher clogging rate, the excess PWP and the saturation front do not have enough time to migrate downstream. Hence, when higher rate of clogging is simulated, the immediate short-term response is bound to show higher magnitudes of PWP due to lesser dissipation of pore-pressure in lesser time, and that is what is manifested in Figure 8(a). Comparatively, Figure 8(b) highlights lesser PWP magnitudes in the entire section when the 3rd stage of clogging is completed with lower clogging rate. It is important to remember that the stated distributions correspond to short-term response of the dam. If the long-term condition is considered, which allows sufficient time for the pore-water pressure to dissipate, the PWP distributions will attain similar magnitudes even for different rates of clogging. Furthermore, Figure 8 shows that for both the high and low clogging rates, the phreatic surface within the earthen dam approximately achieves a similar location. A marginal difference is observed at the downstream face, due to the differential temporal blocking of drainage blanket itself. Even in this case, the marginal difference in the shapes of the phreatic line would fade away under a long-term response scenario. Hence, it can be stated that in the steady-state reservoir condition, beyond the time at which the phreatic surface attains its maximum level within the body of earthen dam, the rate of clogging has marginal effect on the subsequent PWP distribution and shape of phreatic surface.



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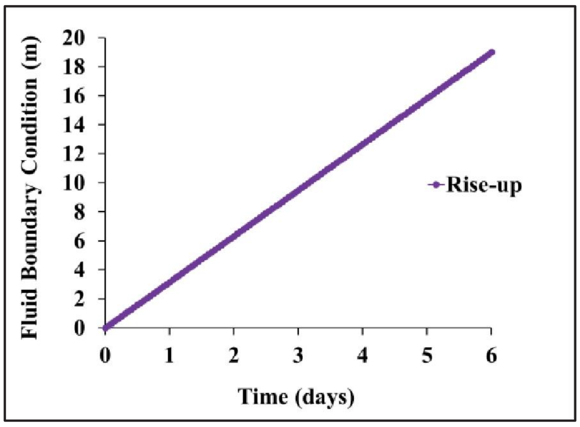
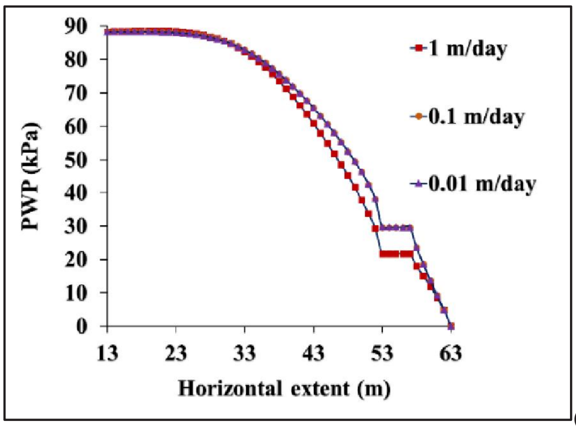


(b)

Figure 6. Transient variation in the upstream reservoir level (a) Drawdown (b) Rise-up

For the reservoir rise-up condition (Figure 7b), it is observed that higher clogging rates result in lower PWP along the base of the earthen dam near the drainage blanket. For all the cases of clogging rates considered in the study, the rate of reservoir rise-up is considered 1.5 m/day. Thus, for the lower rate of clogging (i.e. 0.01 m/day), the reservoir attains its maximum capacity quicker than the complete clogging in the drainage blanket. Hence, for most of the time during the progression of drainage blanket clogging, the reservoir remains full, thereby allowing the excess PWP to migrate towards the downstream within the clogging period itself. On the other hand, for higher rates of clogging, the time required for the reservoir to rise to its full capacity is approximately similar to that required for completing the 3rd stage of clogging. Hence, for higher rates of clogging, the PWP remains concentrated towards the upstream of the dam. Figure 9 aptly displays the variation of PWP within the body of the earthen dam for various clogging rates.



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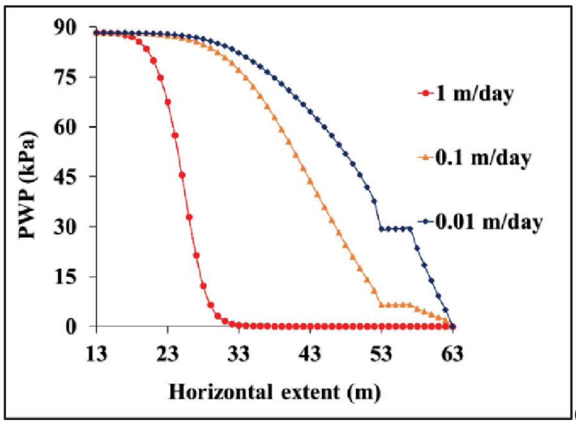

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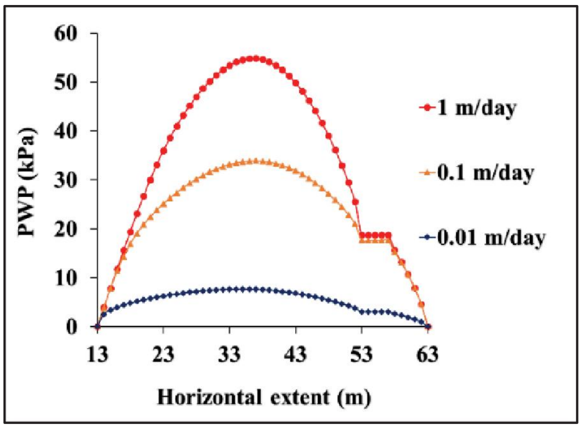
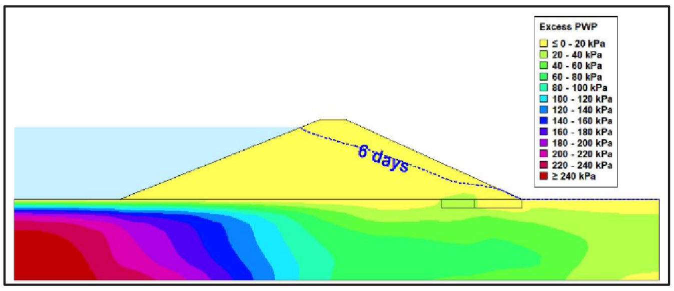


(c)

Figure 7. Influence of clogging rate on the distribution of PWP along the base of the dam near the toe drainage blanket after the 3rd stage of clogging (a) Steady-state reservoir condition (b) Reservoir rise-up condition (c) Reservoir drawdown condition



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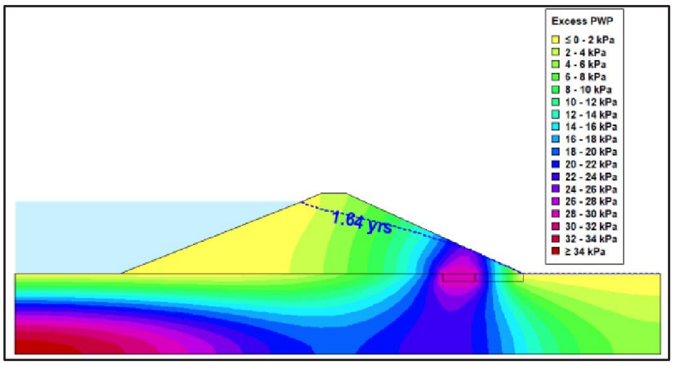
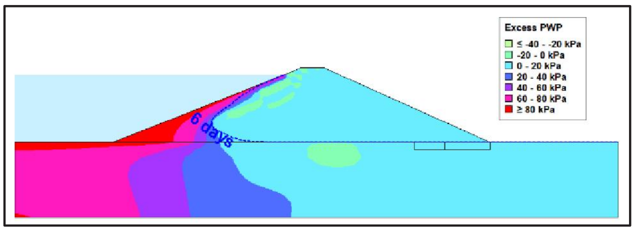


(b)

Figure 8. Influence of clogging rate on the PWP distribution and location of phreatic surface for a steady-state reservoir condition (a) High rate of clogging, i.e. 1 m/day (b) Low rate of clogging, i.e. 0.01 m/day



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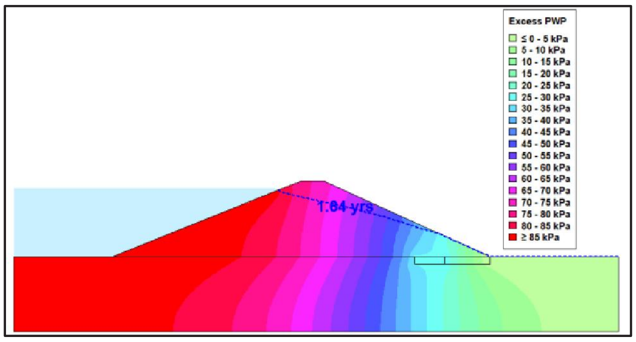
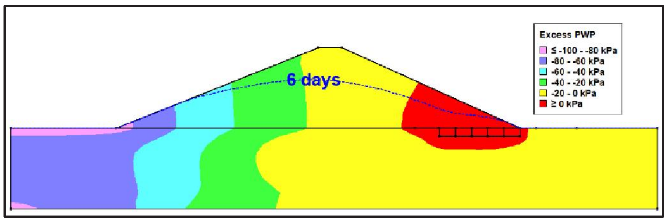


(b)

Figure 9. Influence of clogging rate on PWP distribution and location of phreatic surface for reservoir rise-up condition (a) High rate of clogging, i.e. 1 m/day (b) Low rate of clogging, i.e. 0.01 m/day

In the case of reservoir drawdown, Figure 7(c) shows that higher clogging rates results in higher PWP along the base of the earthen dam. Similar to the reservoir rise-up condition, during the drawdown scenario as well, the rate of drawdown is considered 1.5 m/day. For the higher clogging rate, the complete drawdown of reservoir is achieved at an approximately similar time as required for the completion of 3rd stage of clogging. Hence, the phreatic surface remains at a higher altitude within the body of the dam, and higher magnitude of PWP is observed near the drainage blanket. On the other hand, owing to the low clogging rate, the 3rd stage of clogging takes place at sufficiently higher time, within which significant dissipation of PWP takes through the upstream face of the dam. Thus, for lower clogging rates, lesser PWP is observed throughout the base of the dam. The visual representation of the influence of clogging rate for a reservoir drawdown condition is depicted in Figure 10.



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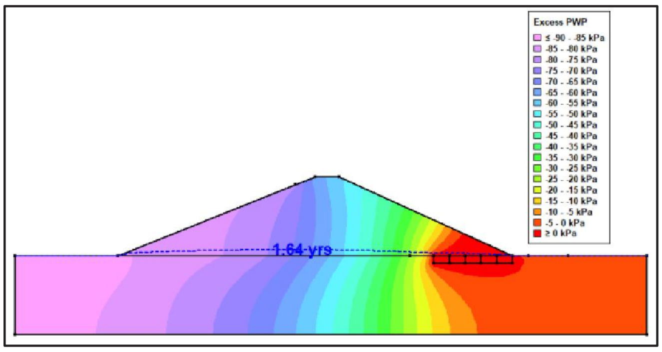

(b)

Figure 10. Influence of clogging rate on PWP distribution and location of phreatic surface for reservoir drawdown condition (a) High rate of clogging, i.e. 1 m/day (b) Low rate of clogging, i.e. 0.01 m/day

4 CONCLUSIONS

This paper presents the influence of clogging rate of horizontal toe drainage blanket on the response of homogeneous earthen dam resting on impervious foundation bed. Finite element based Seep/W and Sigma/W analyses are conducted to estimate and identify the generation of excess PWP under different clogging rates. The influence of clogging is studied on different types of reservoir conditions namely steady-state, rise-up and drawdown conditions. It is observed that the generation of excess PWP is higher for lower clogging rates for the steady-state and rise-up conditions of the reservoir. On the other hand, the generation of excess PWP is lesser for lower clogging rates during the reservoir drawdown condition, and the PWP distribution is concentrated towards the upstream end of the dam. It is concluded that the variation of clogging rate affects the pore-water pressure distribution and location of phreatic surface during the steady-state and transient reservoir operations. However, the effect is predominant when the short-term responses of the reservoir is considered. When a long-term response of the earthen dam is considered, beyond the attainment of the steady-state phreatic surface that occurs after a considerable time-lapse, the effect of clogging rate becomes minimal.

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