Mohr-Coulomb and Hardening Soil Model Comparison of the Settlement of an Embankment Dam

Amjad Hussain Bhutto
Department of Civil Engineering, Quaid-e-Awam University of Engineering Science and Technology, Nawabshah, Pakistan
amjadbhutto62@gmail.com

Shahnawaz Zardari
Department of Civil Engineering, Quaid-e-Awam University of Engineering Science and Technology, Nawabshah, Pakistan
shahnawazzardari@gmail.com

Ghulam Shabir Bhurgri
Department of Civil Engineering, Quaid-e-Awam University of Engineering Science and Technology, Nawabshah, Pakistan
ghulamshabirbhurgri14@gmail.com

Muhammad Auchar Zardari
Department of Civil Engineering, Quaid-e-Awam University of Engineering Science and Technology, Nawabshah, Pakistan
muhammad.auchar@quest.edu.pk

Riaz Bhanbhro
Department of Civil Engineering, Quaid-e-Awam University of Engineering Science and Technology, Nawabshah, Pakistan
riaz@quest.edu.pk

Bashir Ahmed Memon
Department of Civil Engineering, Quaid-e-Awam University of Engineering Science and Technology, Nawabshah, Pakistan
bashir_m@hotmail.com

Muhammad Munir Babar
U.S. Pakistan Centers for Advanced Studies in Water, Mehran University of Engineering & Technology, Pakistan
mmunirbabar.uspcasw@faculty.muet.edu.pk

***Abstract*—In this study, numerical analysis of an embankment dam was carried out to predict settlement behavior with the use of the Mohr-Coulomb Model (MCM) and of the Hardening Soil Model (HSM). The MCM was applied to all material zones of the dam and the HSM was used for four major material zones that occupied significant volume. The settlement response of the dam was similar for MCM and HSM for three material zones (clay core, sandy gravel and random fill), each having a modulus of elasticity (MOE) in the range of 25000 to 50000kPa. However, it was found that after the end of the construction, the MCM showed about 57% and 50% more settlement as compared to HSM when MOE of sandy siltstone varied from 70000 to 125000kPa respectively. The results regarding the dam settlement predicted with the HSM are in agreement with the findings in previous studies.**

Keywords-settlement; embankment dam; hardening soil model; Mohr Coulomb model; modulus of elasticity

I. INTRODUCTION

Embankment dams are being constructed in order to meet the increasing demand of water and electricity. A number of embankment dams are currently being constructed and planned to be raised in the future to resolve water and electricity shortage issues in Pakistan. In order to ensure the safety of embankment dams, in addition to stability [1-2], settlement plays an important role to be estimated with reliability [3-5]. Nowadays, finite element programs are available which can be utilized for the estimation of settlement in the embankment dams. One such finite element program used in geotechnical engineering is the Plaxis 2D which contains a library of different constitutive models that can be utilized for a wide variety of soils. Starting from the linear elastic model, there are several advanced constitutive models implemented in Plaxis 2D [6]. The use of a suitable constitutive model for particular soil and loading conditions depends on the availability of good type of advanced laboratory testing. Normally the budget allocated for the geotechnical investigation of embankment dams is about 1 to 3% of the total cost depending upon the geology of the area [7]. Augmenting the number of advanced tests means that more money would be needed for conducting these tests. As a result, there might be shortage of funds for the actual construction of the dams. For settlement computation of an embankment dam, the modulus of elasticity (MOE) of the soil is a very decisive factor [8]. Having a small amount of money reserved for geotechnical investigation, sometimes, the MOE of foundations soils is not determined experimentally, but it is evaluated indirectly using correlations with experimentally determined material properties, since the stability and settlement response of an embankment dam are usually investigated simultaneously.

Mohr-Coulomb Model (MCM) is widely used for the stability computation of embankment dams [9-11]. The MCM is linear elastic and perfectly plastic model, which requires the following material properties: cohesion, friction angle,

Corresponding author: Amjad Hussain Bhutto

dilatancy angle, unit weight, permeability and modulus of elasticity. However, the settlement of embankment dams predicted with MCM may not be realistic for different soil types. In such situations, there might be the need of using advanced constitutive models depending upon the types of involved soils. The use of advanced soil models for the settlement computation of an embankment dam may require advanced testing which may result to more cost. Therefore, it is necessary to investigate the possible ways to evaluate material properties of an advanced constitutive model based on the mentioned above input parameters of MCM. In order to obtain a reliable estimate of the settlement of an embankment dam by utilizing material properties that are already determined during the geotechnical investigation phase, it might be necessary to find those material zones that may show variation in settlement computed with the MCM in comparison to the response predicted with an advanced constitutive model like the Hardening Soil Model (HSM) [12].

In this paper, an attempt is made based on numerical analysis, to identify those material zones of an embankment dam, which have significant influence on settlement when computed with both MCM and HSM.

II. MATERIALS AND METHODS

Figure 1 illustrates the cross section of Nai Gaj dam that is situated in Dadu district, Pakistan. The main materials used in the dam are: sandy gravel, random fill, clay core. The dam lies primarily on sandy siltstone. The height of the dam is 59m and its length is 1137m. It has been designed as a zoned embankment dam based on principles of geotechnical engineering. There is a series of curtain grouting and consolidation grouting provided under the clay core section of the dam to prevent seepage. The diameter of each of the curtain and consolidation grout is about 76mm. The length of the curtain grouting is 16m while the length of consolidation grouting is 45m. Numerical analysis of the settlement of the dam was performed on the cross section (Figure 1) using the finite element program Plaxis 2D [6].

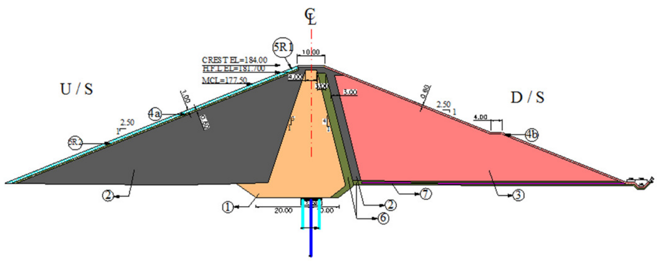

Fig. 1. Cross section of Nai Gaj dam

The cross section of the dam shows that there are four zones which occupy the most of the dam's volume. These zones are: clay core, sandy gravel, random fill, and sandy siltstone. Now, it is important to investigate the effect of these zones on the overall settlement of the dam. For this purpose, MCM and HSM are used for numerical analysis. Since the settlement of the dam depends on the magnitude of the MOE of different soil types, therefore, the effect of variation of MOE of the four major zones of the dam is investigated. For each of the three materials (clay core, sandy gravel and random fill), the MOE varies from 25000 to 50000kPa separately. While for the fourth material zone (sandy siltstone), the MOE varies from 70000 to 125000kPa. Whenever the effect of a particular material zone on settlement is investigated, the properties of the other materials are utilized as presented in Tables I and II.

TABLE I. MATERIAL PROPERTIES OF MCM FOR EMBANKMENT AND FOUNDATION OF THE NAI GAJ DAM

Material type	Saturated unit weight (kN/m^3)	Cohesion (kN/m^2)	Friction angle (deg)	MOE (kN/m^2)	Permeability (m/day)
Clay	18.85[13]	9.57[13]	30[13]	49795[13]	0.00263[13]
Sandy gravel	21.5[14]	0	37[15-17]	50000[18]	86.4[19]
Random fill	18.85[13]	0	34[13]	47880[13]	0.263[13]
Washed gravel	21.5[14]	0	37[15-17]	45000[20]	864[21]
D/s slope protection	19.5[22]	0	34[15-17]	40000[23-24]	8640[21]
Riprap	19.5[13]	0	34[13]	40000[23-24]	8640[21]
Sand filter	18.85[13]	0	36[13]	40220[13]	26.33[13]
Drainage blanket	21.5[14]	0	37[15-17]	45000[21]	864[21]
Sandy siltstone	20.4[13]	12[13]	29[13]	70000 to 125000 [25]	0.0063[13]

TABLE II. HSM PARAMETERS FOR THE FOUR MAIN ZONES

Material type	E_{50}^{ref} (MPa)	E_{oed}^{ref} (MPa)	E_{ur}^{ref} (MPa)
Clay core	50000	50000	150000
Random fill	50000	50000	150000
Sandy gravel	50000	50000	150000
Sandy siltstone	125000	125000	375000

The MOE of sandy siltstone was evaluated from its uniaxial compressive strength using the following correlation [25]:

$$E/q_u = 200 \text{ to } 500 \qquad (1)$$

where E is the MOE (kPa) and q_u is the uniaxial compressive strength (kPa).

Most of the results show that the value of the uniaxial compression strength of sandy siltstone is less than 2MPa. The minimum value is 0.35MPa [13]. The following values of MOE of sandy siltstone are used in this study:

$$E = 200 \times 0.35 = 70000\text{kPa (minimum value)} \qquad (2)$$

$$E = 350 \times 0.35 = 125000\text{kPa (maximum value)} \qquad (3)$$

Consolidation analysis was performed to compute the settlement of the dam. In numerical modeling, the dam was constructed in a pace of three meters in thirty days. Figure 2 shows the finite element model whose horizontal boundaries are given an extension of one hundred meters on either side to reduce the influence of boundaries on the computed results. Refinement of the mesh (Figure 3) was performed until the average size of the element was 2.148m, which showed no influence on the results. Ground water level is marked fifteen meters below the surface and maximum flood water level is at 56.6m (Figure 4).

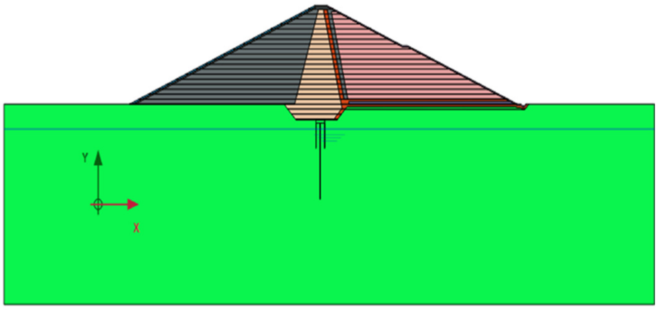

Fig. 2. Finite element model of Nai Gaj dam

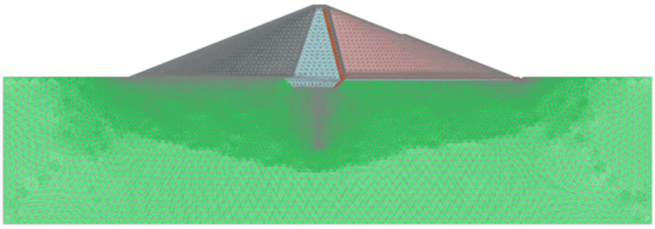

Fig. 3. Finite element mesh of Nai Gaj dam

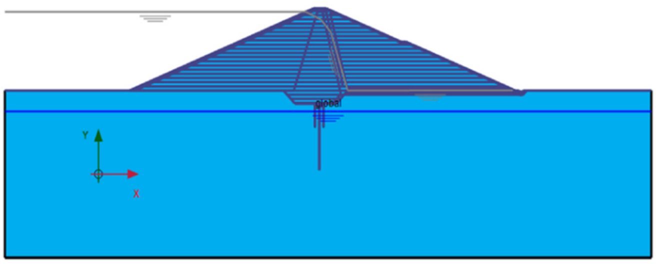

Fig. 4. Maximum water level in the Nai Gaj dam

III. RESULTS AND DISCUSSION

A. Comparison of Dam Settlement with the Use of MCM and HSM

All materials are modeled with the MCM (condition 1). Each of the four materials (clay core, sandy gravel, random fill and sandy siltstone) is modeled separately with HSM, and the rest are modeled with MCM (condition 2). The calculations of settlement of the dam were performed for the end of construction (EC) and after the filling of reservoir (AFR) conditions. The settlement response of the dam computed with MCM and HSM are compared for the EC and AFR in Figures 5-12.

From the results (Figures 5-10) it is concluded that there is less variation in settlement computed with the MCM and HSM for three of the major material zones (clay core, sandy gravel and random fill) at EC and AFR conditions. For clay core, random fill and sandy gravel, the MCM overestimates the shear strength. Therefore, the settlement predicted by the MCM was slightly lower than the one computed with the HSM. On the other hand, for sandy siltstone (foundation), the settlement predicted with the MCM is higher than the one predicted with HSM.

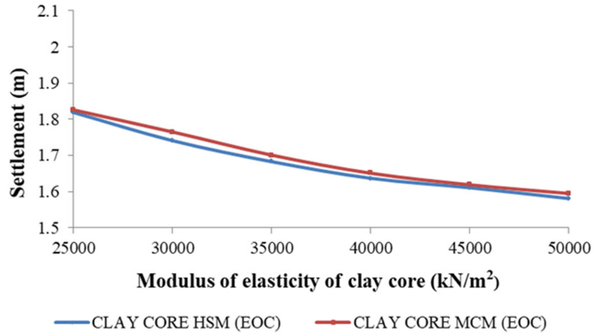

Fig. 5. Comparison of dam settlement at EC computed with MCM (condition 1) and HSM applied to clay core only (condition 2)

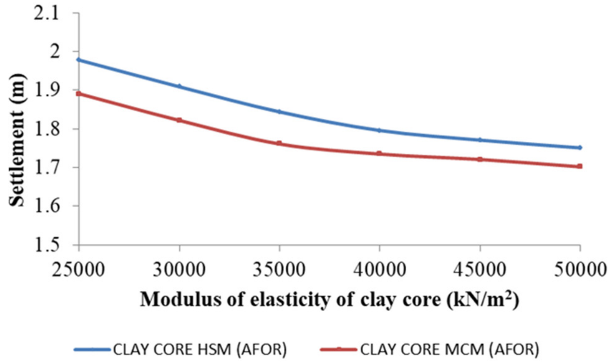

Fig. 6. Comparison of dam settlement at AFR computed with MCM (condition 1) and HSM applied to clay core only (condition 2)

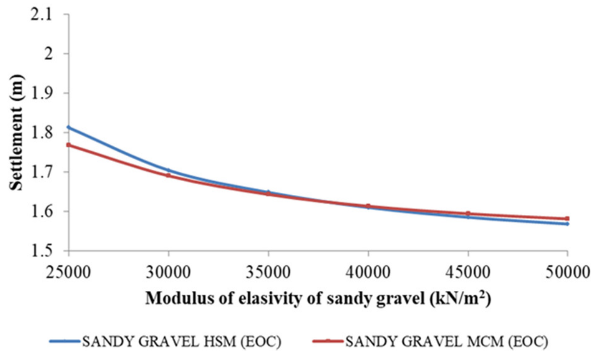

Fig. 7. Comparison of dam settlement at EC computed with MCM (condition 1) and HSM applied to sandy gravel (condition 2)

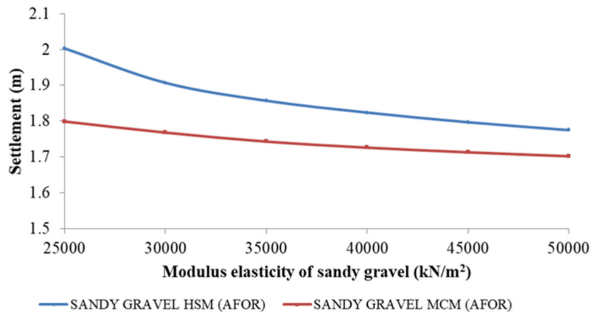

Fig. 8. Comparison of dam settlement at AFR computed with MCM (condition 1) and HSM applied to sandy gravel (condition 2)

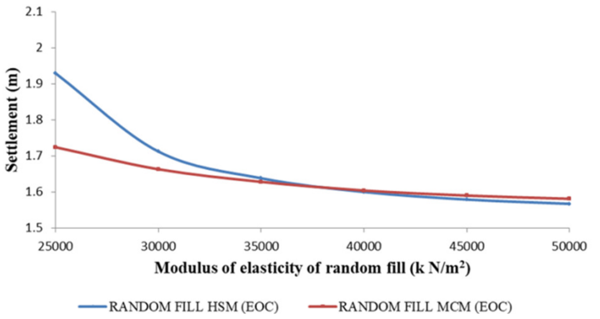

Fig. 9. Comparison of dam settlement at EC computed with MCM (condition 1) and HSM applied to random fill (condition 2)

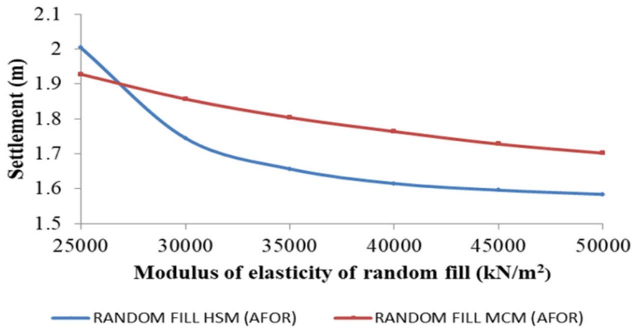

Fig. 10. Comparison of dam settlement at AFR computed with MCM (condition 1) and HSM applied to random fill (condition 2)

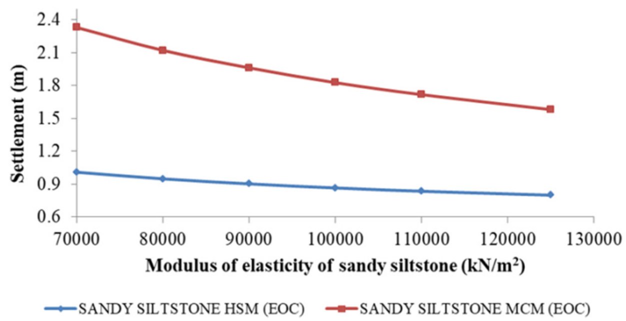

Fig. 11. Comparison of dam settlement at EC computed with MCM (condition 1) and HSM applied to sandy siltstone (condition 2)

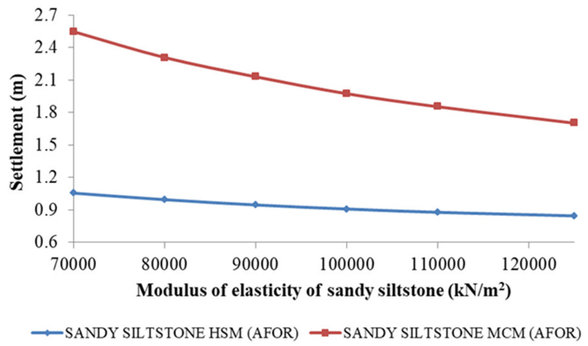

Fig. 12. Comparison of dam settlement at AFR computed with MCM (condition 1) and HSM applied to sandy siltstone (condition 2)

B. Percentage Increase of Settlement Predicted with MCM for the EC and AFR Compared with HSM

Figure 13 shows the comparison of dam settlement computed with the MCM and HSM for EC and AFR conditions. The MOE of sandy siltstone varies from 70000 to 125000kPa. It is observed that for EC, the MCM showed 56.65% and 49.40% more settlement than the HSM when the MOE of sandy siltstone increased from 70000 kPa to 125000kPa respectively. It is observed that for AFR, the MCM showed 58.85% and 50.30% more settlement than the HSM when the MOE of sandy siltstone increased from 70000kPa to 125000kPa respectively.

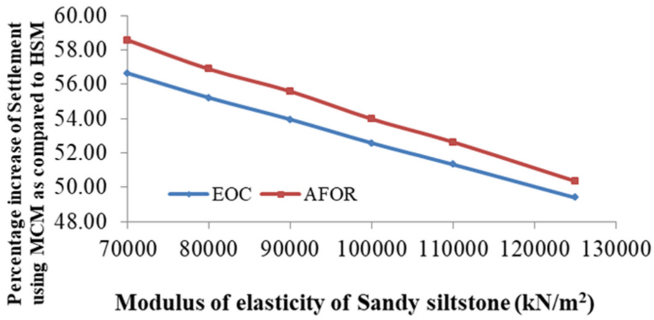

Fig. 13. Increase percentage of MCM as compared to HSM when the MOE of sandy siltstone varied from 70000 to 125000kPa

The settlement of the dam was calculated only at the crest of the dam. From the results, it is concluded that the sandy siltstone (foundation) has more influence on settlement as compared to the other zones of the dam. According to a study on 134 such embankments, it was found that most of the embankments settled as high as 1% of the dam height [25]. As mentioned above, the sandy siltstone (foundation) is sensitive to settlement when predictions were made with the MCM and HSM. The MCM showed a settlement of 2.5m (AFR) when the MOE of sandy siltstone is 70000kPa. This shows that the predicted settlement with the MCM is about 4.2% of the dam height. The MCM showed a settlement of 1.7m (AFR) when the MOE of sandy siltstone is 125000kPa. This shows that the predicted settlement with the MCM is about 2.9% of the dam height. The HSM showed a settlement of 1m (AFR) when the MOE of sandy siltstone is 70000kPa, with a predicted settlement with MCM of about 1.69%, and a settlement of 0.8m (AFR) when the MOE of sandy siltstone is 125000kPa, showing predicted settlement of about 1.35%. This implies that the 0.8m settlement of the dam is considered to be a reasonable estimate.

IV. CONCLUSIONS

Numerical analysis of an embankment dam was conducted to adopt a reasonable magnitude of MOE of those zones of the dam, which have major influence on settlement. Dam settlement was computed with Morh-Coulomb Model (MCM) and Hardening Soil Model (HSM), and the results were compared. The results suggest that out of the four major zones of the dam (clay core, sandy gravel, random fill and sandy siltstone), the sandy siltstone has the most influence on the settlement of the dam for both MCM and HSM. The results suggest that the settlement predicted with the HSM is in match with the findings in similar studies.

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