USING EARTH PRESSURE INSTRUMENT DATA TO EXAMINE THE SAFETY OF EARTH DAMS AGAINST ARCHING AND SHEAR FAILURE

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ABSTRACT

Stress state in earth dams is one of the most important parameters to evaluate dam safety, especially at the first impounding of the dam reservoir for selecting the optimum speed of filling, and during the operational time to evaluate the long-term stability of the dam and its foundation. In zoned earth dams, arching control is very important because stress inside the core materials and in adjacent to the core-filter interface is commonly reduced and fragile deformations may occur. In this condition the hydraulic fracturing and cracking, and consequently, the core failure is also possible. In addition to arching control, ensuring the stress levels inside the dam body and its foundation to be in a safe mode is essential in critical conditions such as earthquake or flood occurrence. One way for measuring and monitoring the stress values in earth dams is using the pressure cells in different part of the dam. Pressure cells are available in different types and can record the amount of the total stress generated by the forces applied to the soil body. However, due to the various events, such as stress concentration and installation issues; it is necessary to modify the recorded values of the stresses by soil pressure meters. In this paper, an earth dam in Iran, namely Silveh dam, and its recorded instrument data, are considered. Then by providing a solution, the raw instrument data are modified and the arching phenomenon is studied.

INTRODUCTION

Silveh Dam is a recently constructed zoned earth dam located about 12 km Northwest of Piranshahr city in the Western Azerbaijan Province, Iran. The dam body is placed on a wide valley which comprises a coarse-grained alluvial deposits with maximum of 65 m depth in right bank and limestone or schist rock in left bank, underlain by a layer of lightly metamorphosed limestone and shale with lenses of slate, metamorphic sandstones, and powdered layers of schist and mica schist (Garakani et al. 2017). The capacity of the dam reservoir, at its normal water level (1573.5 m.a.s.l), is about 84 mcm. With a crest level of 1579 m.a.s.l, the maximum height of the dam is approximately 89 m from foundation and its crest length is near 720 m (Jafarzadeh et al. 2018a). The fill material properties are summarized in Table 1. In this study, the results of maximum cross section (i.e., section 2-2) is analyzed (Jafarzadeh et al. 2018b, Jafarzadeh et al. 2019, Tournier et al. 2019). This section is shown in Figures 1 and 2.

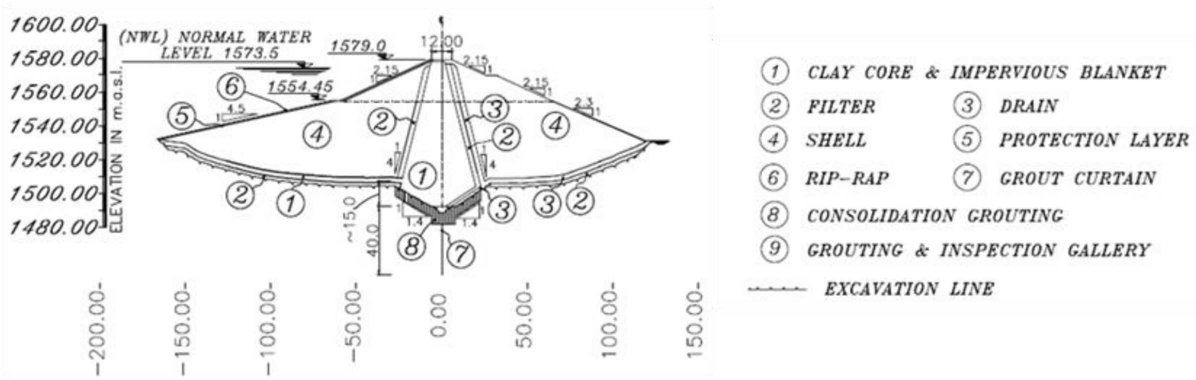
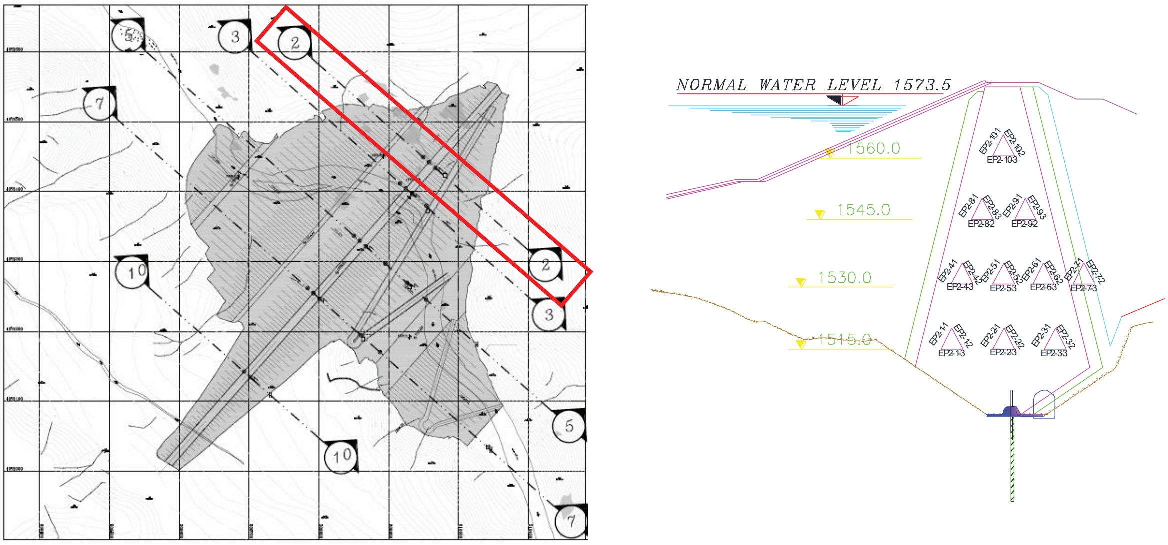


Figure 1 : The maximum height cross section of the Silveh dam.



(a) (b)

Figure 2 : (a) Plan of Silveh dam, and (b) Location of the earth pressure instruments at section 2-2.

Table 1 : Shear strength and density properties of the fill materials.

Material	Cohesion, c (kPa)	Internal friction angle, ϕ (deg)	γ_{sat} (kN/m^3)	γ_{wet} (kN/m^3)
Core (CD)	6	33	-	19
Core (UU)	28	5	20	-
Shell	7	41	22	20
Filter	0	32	22	20
Drain	0	35	22	20

1. STRESS STATE IN DIFFERENT LEVELS OF THE SILVEH DAM

To measure the stress levels through the dam body, a set of cell pressures has been installed at some points for different sections and levels of the Silveh dam. For this purpose, at each of these points, three pressure plates are utilized (Figure 3). Two pattern of installation are used for the cell pressure of the section 2-2 of the dam as shown in Table 2. By applying the solid mechanics' relationships, two-dimensional vertical and shear stresses can be derived (Abgeer 2019). The results are shown in Figure 4, which indicate all cell pressures reported high level of earth pressures during the construction phase, following by slight changes during the fluctuations of the reservoir water level.

(a) (b)

Figure 3 : Position of the stress instruments based on stress petal method, (a) Pattern A, and (b) Pattern B

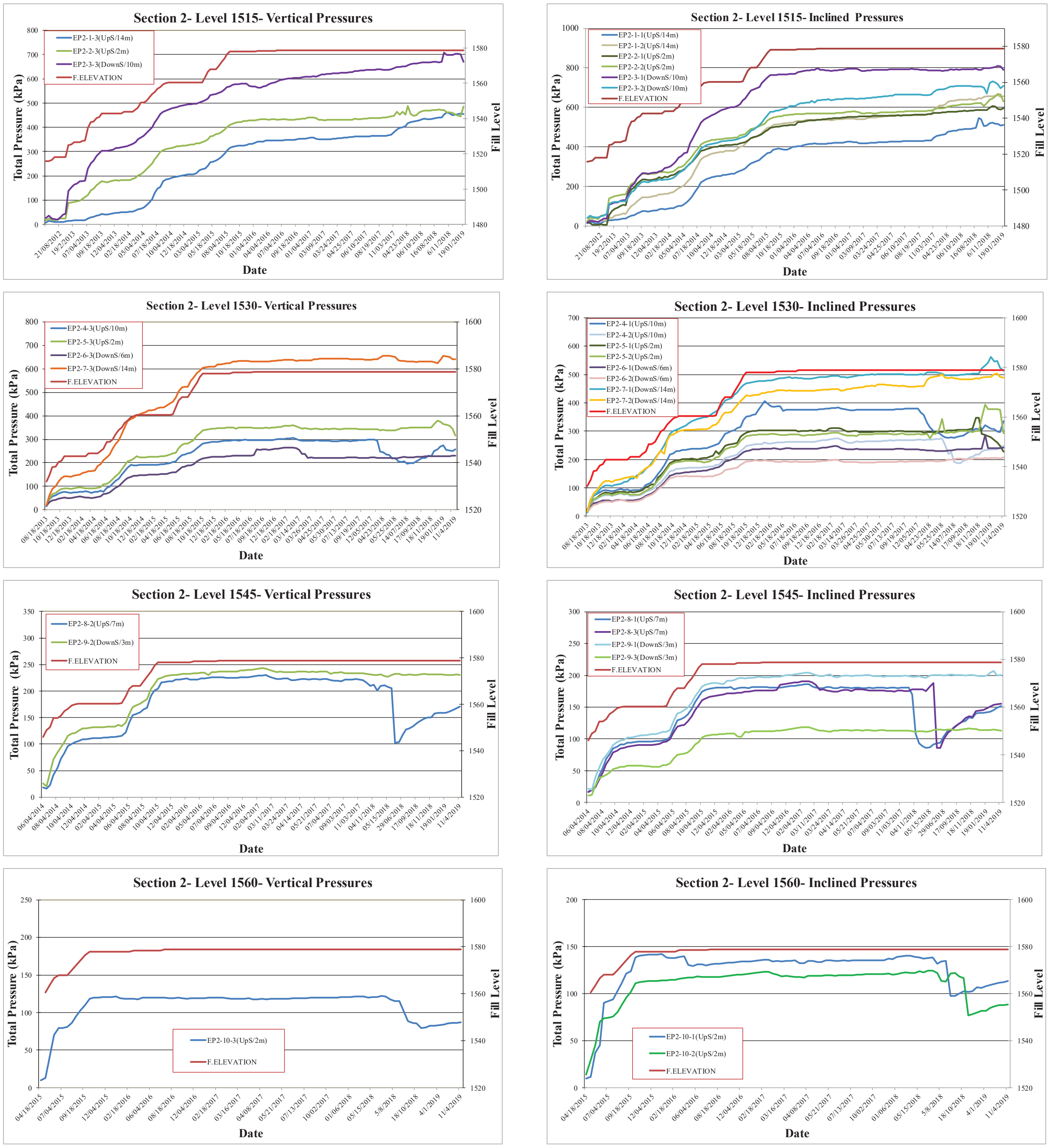


Figure 4 : Vertical and inclined pressure at dam body on four levels in section 2-2 of Silveh dam.

Table 2 : The installation pattern of different earth pressure instruments in Silveh dam body.

EP instruments name	Pattern	EP instruments name	Pattern
2-1	B	2-6	B
2-2	B	2-7	B
2-3	B	2-8	A
2-4	B	2-9	A
2-5	B	2-10	B

2. PREDICTION OF THE ARCHING COEFFICIENT AT DIFFERENT LEVELS AT SECTION 2-2

The arching is created due to the lack of complete transfer of the earth pressure between the embankment layers, which reduces the effective stresses in the soil, and increasing the probability of hydraulic fracture in the dam body. This phenomenon mainly occurs in the core of inhomogeneous earth dams that is mainly originated from the consolidation of the core after the construction phase. Some parts of the dam body (e.g., filter, drain, and shell) do not have the consolidation behavior and act as side restrains to core settlement. Accordingly, weight of the core materials tends to transfer on the side filters and the effective stress in the core becomes less than the overburden pressure (i.e., γh). Arching usually occurs more intensively in low-thickness cores. In addition to the core-filter interactions inside the dam body, the foundation settlement beneath the core can cause arching. The arching coefficient, A, is commonly defined as the ratio of the measured vertical pressure to the overburden pressure:

$$A = P_v / \gamma h \tag{1}$$

where, P_v is the actual vertical pressure (commonly recorded by the earth pressure instrument) γ is the soil unit weight, and h is the height of the overburden soil. The smaller arching coefficient indicates that the stress from the dam body is not transferred to the lower layers, and values close to one mean the appropriate pressure transfer of the upper layers to the lower parts. In addition, the arching coefficient higher than one indicates load transfer from other parts of the body to the stress measurement point. The high ratio of arching can cause longitudinal cracks in the dam core, which increases the probability of piping. Another adverse effect is the effective stress reduction that can cause hydraulic fracture and scouring of the dam body after impounding and raising the pore water pressure inside the core. The arching coefficients in the different levels of section 2-2, based on the recorded vertical earth pressures are shown in Figure 5.

The notable point about the low coefficients at some levels is the arching coefficient decreases when the embankment height relative to the earth pressure instrument level is only a few meters (less than 10 meters). Nevertheless, the arching occurs usually when the stress of the dam body is not transferred to the lower layers and imposed to the stiff layers around the core. A phenomenon found in many instruments installed in earth dams is the "Local Arching" that is due to the inadequate transfer of vertical stress to the soil layers. As a result, the instrument values become much lower than the corresponding real values. Many researchers have studied this issue, although no specific solution has been proposed in preventing this phenomenon (Sherard 1986, Shahbazian et al. 2007, Elmi & Mirghasemi 2013). Based on experiences in the design of earth dams, it can be assumed that the arching is negligible when the embankment height is up to a specific height of filling namely, Zo, above the earth pressure instrument, and the predicted earth pressure is equal to the γh. For the heights more than Zo, Elmi & Mirghasemi (2013) defined the stress reduction ratio (k) in earth pressure instrument caused by arching, as:

$$\mathrm{k} = \frac{\gamma \mathrm{Zo} - \mathrm{S_t}}{\gamma \mathrm{Zo}} \tag{2}$$

where St is the recorded stress values. Since k is considered constant for any installed instrument, it is determined at the embankment height is up to the height of Zo above the instrument level. Then, the earth pressure is modified according to the following equation for the other height of the embankment:

$$S_c = \mathrm{k}\gamma \mathrm{z} + S_t \tag{3}$$

where S_c is the actual stress at the instrument location in the dam body and z is the height of the embankment above the level of the instrument. In this research, by considering the specific characteristics of the Silveh dam and taking into account the engineering judgements, the Z_o height was considered as 15m. As a result, the modified arching coefficient is calculated at different levels and is shown in Figure 5.

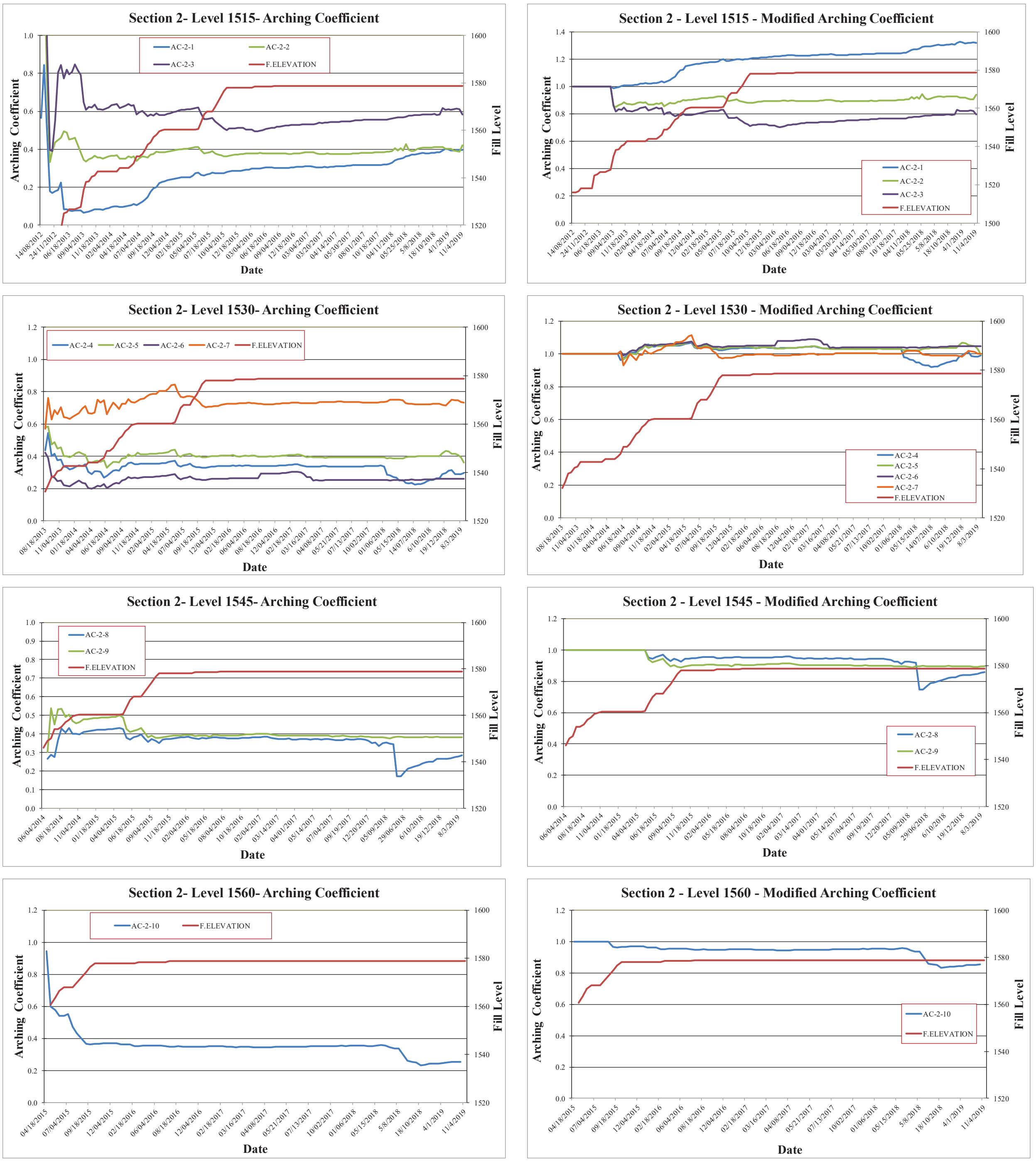


Figure 5 : Arching coefficient and modified arching coffecient in four levels of section 2-2.

3. STRESS STATUS IN CRITICAL PLANE AND COMPARISON WITH SHEAR FAILURE CRITERIA

By representing the stress points on the critical plane at four height levels of section 2-2 and comparing them with the Mohr-Coulomb (M-C) failure criteria, one can predict the possibility of giving the failure conditions. The critical stress plane has an angle of 45+ϕ/2, where ϕ is the internal friction angle of the soil. The normal and the shear stresses on the critical plane of stress can be obtained as:

$$\sigma_n = \frac{1}{2}(\sigma_1 + \sigma_3) + \frac{1}{2}(\sigma_1 - \sigma_3)\cos^2(45 + \varphi/2) \tag{3}$$

$$\tau_C = \frac{1}{2}(\sigma_1 - \sigma_3)\sin^2(45 + \varphi/2) \tag{4}$$

Consideration of soil conditions, mainly core clay consolidation or seepage of the water through it, is necessary while determining stress values to calculate the critical stresses. For example, in the initial stages of the dam construction, the consolidation process is not fully completed and the critical stress values must be calculated by considering the short-term shear strength parameters and corresponding soil failure criterion. Clearly, for the fully consolidated conditions, drained soil properties must be attended. The shear failure stress, according to the Mohr-Coulomb criterion, is obtained using the following equation:

$$\tau = c + \sigma_n \tan \varphi \quad (5)$$

The stress state charts at different stages of the construction process at four levels of the dam body in section 2-2 with consideration of the M-C failure criteria are shown in Figure 6. It should be noted that at the end of the construction phase, the consolidated undrained (CU) parameters were considered for the core materials assessment. It is considered for dam core, the cohesion of 28 kPa and 5 ° internal friction angle, and for the filter, zero adhesion, and 32° internal friction angle. As the embankment level increases, the overall stresses at the instrument locations slowly increase. Similarly, the shear stresses values are increased to give the failure state of the shear stress. Finally, the soil materials show softening or hardening behavior depending on the initial state of compaction (for granular soils) or the pre-consolidation condition (for the cohesive soils).

In section 2-2, the stress at the 2-1 and 2-9 instruments crossed the M-C failure line, although the soil materials at both points were in the hardening phase. This status indicates that the M-C failure line underestimates the actual conditions. As a result, in this case, either the actual shear strength parameters of the soil were higher than the considered values, or the recorded data were not reliable. According to the data presented in Figure 6, it is observed that after the initial impounding in early 1396 m, almost none of the tools reported the shear failure and the dam body in section 2-2 is appraised in a safe condition.

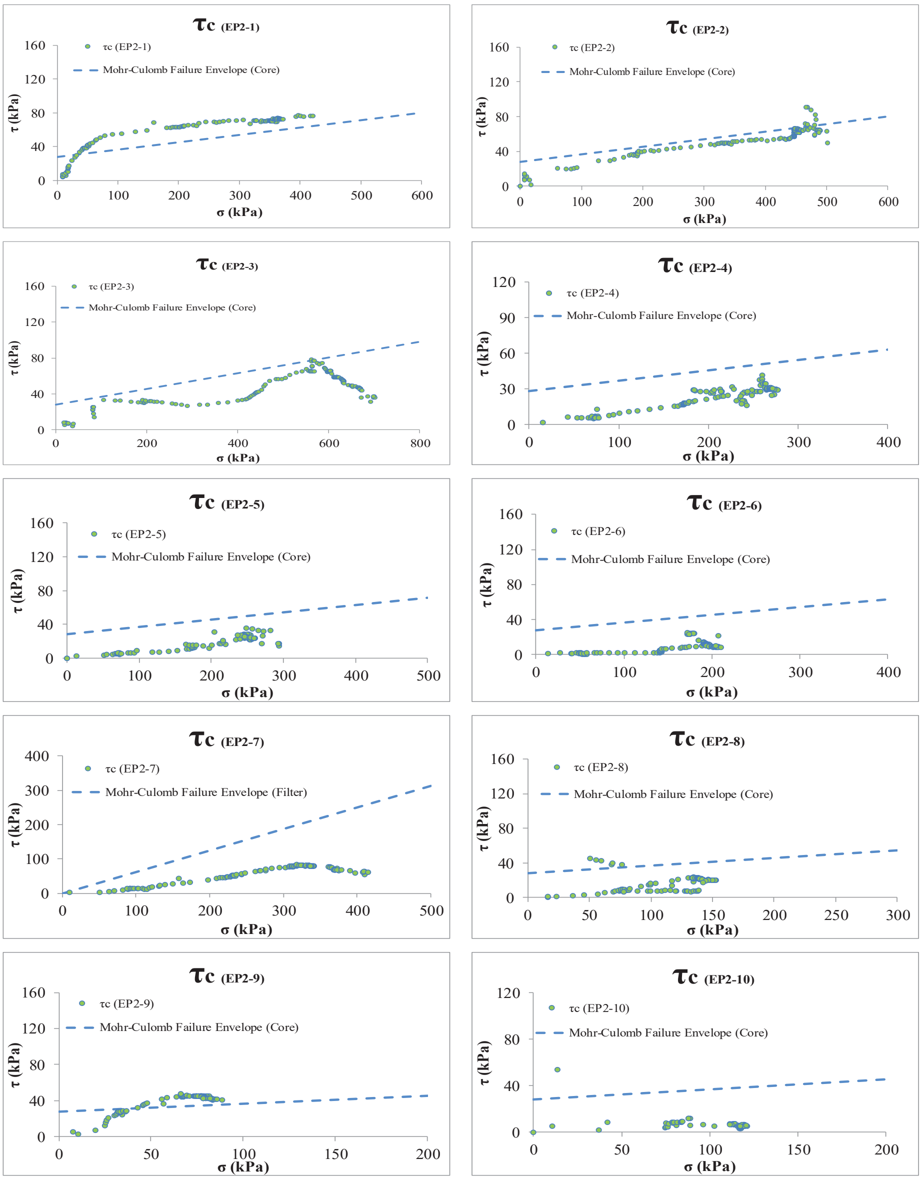


Figure 6 : Stress state on critical plane in section 2-2 in front of the failure criteria of Mohr-Coulomb.

4. CONCLUSION

In this paper, the stress values inside the Silveh earth dam were studied by considering the earth pressure data. Accordingly, one of the dam's highest sections was selected, and the values of the stresses at four elevations (with a 15m difference together) in the body were studied. Since the value of the instruments differs mainly from the actual stress values due to some issues (e.g., effects of the construction works, local arching, and stress concentration) this paper presents a method to modify the stress values. Then by using the modified stress values; the arching ratio was evaluated and the main stress values on the critical planes were compared with the Mohr-Coulomb criteria. The results show that the proposed relationship is in good agreement with the analytical predictions. Additionally, the studied section of Silveh dam was shown to be in a safe condition against arching and shear failure.

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