
THE EVALUATION OF CHANGES IN PERMEABILITY AND CHEMICAL COMPOSITION OF GYPSEOUS SOILS THROUGH LEACHING IN SOUTHERN MASHHAD, IRAN

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Abstract: Solubility is the main problem of gypseous soils. In dry state, these soils are resistant and have good engineering properties. However, when saturated by rainwater or rising groundwater table, the minerals in these soils are washed out, making the structures built on them prone to subsidence. In the recent decades, buildings constructed in southern area of Mashhad Metropolitan, Iran, have been widely faced with this problem. Since permeability and chemical composition of these soils are varying in time due to the solubility of gypsum, the current study is an effort to determine hydraulic and chemical properties of the soluble soils of the area and their changes throughout the leaching process. Seven soil samples with different gypsum contents were selected from the area for analysis in four major groups of tests including physical tests (grain size analysis, Atterberg limits and specific gravity), chemical tests (chemical analysis of soils, Total Dissolved Solids (TDS), Electrical Conductivity (EC), and leaked water chlorine), hydraulic tests (permeability and solubility) and statistical analysis to determine the depth of maximum gypsum and sulfate ion concentration. Changes in the mentioned parameters were investigated through a 5-day leaching process. In the early stages of the tests, high variability was observed in permeability coefficient and concentration of minerals in the soil. These changes were gradually decreased and tend to constant values.

Keywords: *Gypseous soils; solubility; leaching; permeability..*

1.0 Introduction

The presence of large quantities of gypsum in the soils of southern Mashhad is the major civil engineering problem of the area. The main problem is the hollowness of gypseous soils. These soils are yellow in color and are abundantly found with large gypsum crystals in the area. Gypseous soils are typically resistant in dry conditions due to the cementing effect of gypsum. However, upon the addition of moisture, due to partial or complete saturation of the soil, soluble substances dissolve and reduce the resistance of the soil substantially. This problem becomes more severe when the water flow inside the

soil results in soil mass loss due to the leaching of gypsum. Leaching is a process in which the natural or artificial penetration of fluids in soil results in solution and washing of soil soluble components (Al-Zgry, 1993).

Gypsum is the hydrous calcium sulfate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and is present in different crystalline forms in soils. This mineral has solubility of 2.6 g/l when the inter-granular water is 25 degrees Celsius and has 0.101 MPa pressure. Moreover, its solubility is also a function of the presence of other salts in the soil (Kovda, 1954). Solubility of gypsum is increased by the presence of chlorides especially Sodium and Magnesium chlorides. Gypsum solubility is less than other chlorides and sulfate salts and is highly dependent on the flow velocity and the permeability of the porous media. The term “soluble salts” usually refers to salts with more solubility than gypsum (Eswaran & Gong, 1991). Based on previous research, smaller soil grain size and lower water penetration rate, significantly reduces the gypsum solubility rate. Therefore, gypseous soils with coarser textures such as sands are more susceptible to leaching hazards compared to clays or silty clays (Tatlari, 1996).

Several studies have been done on the properties of gypseous soils in southern Mashhad. However, in spite of the fact that one of the most important problems in the area is the subsidence of the gypseous soils, no study so far has addressed the changes in chemical composition and permeability of these soils due to solution and leaching. The aim of this research is to evaluate the effects of leaching on the changes in the chemical composition and permeability of gypseous soils in the area. Nashat (1990) studied the effects of leaching process under different hydraulic gradients and stress levels on samples taken from three areas in Iraq with highest amounts of gypsum. They observed that hydraulic conductivity has a fluctuating decreasing trend in time. These fluctuations resulted in the enlargement of void spaces, removal of gypsum and blockage of some of the flow paths due to the leaching-induced collapses.

Besides from the general increasing trend in the leakage, there were instances where the leakage coefficient is decreased by the leaching of salts. For example, after initial saturation, this decrease is due to the ion exchange and then due to the weakening of cementing bonds, dispersion of soil particles and subsidence under the static load. In other words, the major factor in desalination of coarse grained soils is their high permeability. In contrast, in soils with low permeability, the progression of leaching increases hydraulic conductivity. Desalination of soils under a load similar to the in-situ stress might cause 10 to 100 times more decrease in the leakage coefficient. In this situation, hydraulic conductivity changes depend on several factors such as initial quantity and composition of salts, physical and mechanical properties of the soil, leakage conditions, leaked water composition and pressure (Nejadhashemi, 1997).

Namiq and Nashat (2011) studied the effects of leaching on volume changes of gypseous soils in northern Iraq, using uniaxial compression test in Row cell. They

showed that consolidation tests and traditional interpretation methods are not practical for gypseous soils and derived a new form of stress-strain relationships for these soils. Al-Qaissy (1989) conducted extensive laboratory tests on soils with 75% Gypsum in Al-Thartha, Iraq. His experiments included leaching-permeability tests with different pre-consolidation ratios, stress values and soil saturation time. The results showed that the void ratio remains constant for normally consolidated samples, while in pre-consolidated samples, it increases proportional to the pre-consolidation ratio and saturation time.

Keren and O'Connor (1982) showed that the increase in the amount of gypsum particles smaller than 44 micrometers results in a significant decrease of hydraulic conductivity in soil while particles with 0.25 to 1 micrometers had no impact on it. Furthermore, although the hydraulic conductivity is usually increased during leaching, an opposite condition might occur, in which, due to the mechanical blockage of small gypsum particles, hydraulic conductivity is decreased.

Boyadgiev (1996) studied gypsum plateaus of Euphrates in Syria and found that soils with 10 to 35% gypsum had much higher permeability compared to the samples without gypsum. Moreover, water velocity in gypseous soils was higher compared to non-gypseous ones which classify them as moderate to highly permeable. Sometimes, these soils show very low permeability which is attributed to the compacted layers in soil profile. This has been observed in irrigated gypseous areas where leached gypsum is transferred deeper in soil. In particular conditions, this produces compacted petro-gypsic profiles which contribute to the decrease in hydraulic conductivity (Tatlari, 1996). Keren and O'Connor (1982), showed that gypseous soils have a wide range of hydraulic conductivity variations from 0.12 to 10 m/day. Furthermore, the presence of large gypsum crystals may cause soils to have permeability conditions similar to sandy soils.

2.0 Materials and Methods

The study area is located in south of Mashhad, Iran, between 59° 26' to 59° 36' E longitudes and 36° 13' to 36° 20' N latitudes, with an average elevation of 1140 meters. Figure 1 shows map and satellite image of Mashhad and the study area with samples locations.

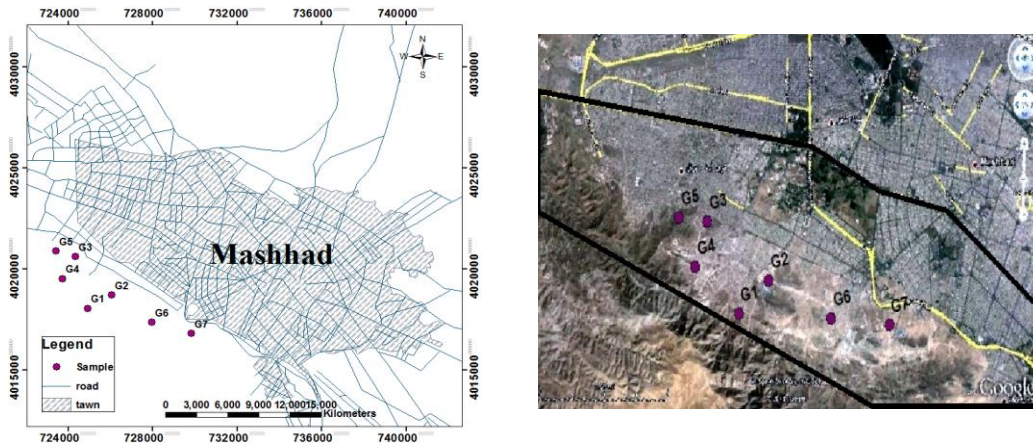


Figure 1: Map and satellite image of Mashhad and the study area with samples locations (satellite imagery form Google Earth®)

Our study was done in four major stages. At first, physical tests were done to analyze grain size and determine Atterberg limits and dry density. In the second stage, chemical tests were conducted first on the soil samples and then on the water leaked from soil samples during leaching process. In soil sample tests, gypsum, sulfate and chlorine quantities, pH, TDS and EC were determined. Leaked water analysis was done to determine TDS, chlorine and calcium hardness (CH). In the third stage, hydraulic tests were carried out to measure constant head permeability and solubility of samples. Finally, depth of maximum gypsum and sulfate ion concentrations were determined for the study area.

3.0 Results and Discussion

3.1 Physical Tests

Physical tests on samples were done in accordance with ASTM standard and the summary of the results is presented in Table 1. As depicted in the table, samples G2 and G6 which had the highest amount of gypsum, had the highest plasticity limit and liquid limit which shows the effect of gypsum on these parameters. Due to the high abundance of gypsum and hollowness of the soil, the dry density of all samples were extremely low, with some being 1 g/cm^3 .

Table 1: The results of physical tests on soil samples

Name	Unified Soil Classification	PL (%)	LL (%)	PI (%)	Dry Density (gr/cm ³)
G1	SM	19.8	29.8	10	1.22
G2	SM	22.6	39.2	16.6	1.24
G3	ML	16.9	30.3	13.4	1.27
G4	SC	NP	22.3	NP	1.32
G5	SM	NP	29.1	NP	1.40
G6	ML	27.3	56.0	28.7	1.00
G7	CL-ML	19.5	27.2	7.7	1.14

3.2 Chemical Tests

3.2.1 Chemical Tests of Soil Samples

To determine the chemical composition of soil samples and the potential effects of its components on the amount of gypsum solution, soil samples were chemically analyzed to obtain the amount of gypsum, sulfate ion, pH, TDS and EC. The results of these tests are summarized in the Table 2.

Table 2: The results of chemical tests of soil samples

Sample	Gypsum (CaSO ₄ ·2H ₂ O%)	SO ₃ (%)	Cl ⁻ (%)	pH	TDS (%)	EC (Mmohs/cm)
G1	2.85	6.780	0.003	8.03	2.6	2.07
G2	57.31	33.080	0.002	8.12	3.6	2.01
G3	3.87	20.320	0.030	8.27	4.0	2.56
G4	3.77	22.330	0.002	8.17	4.1	2.60
G5	2.91	3.029	0.009	8.08	2.1	1.88
G6	42.75	39.550	0.005	8.02	2.7	1.80
G7	4.60	9.150	0.003	8.01	3.0	1.75

3.2.2 Chemical Tests on the Leaked Water from Soil Samples

For leaching, each sample was first remolded to a perforated cell with 10.12 cm in diameter and 12.17 cm length and then connected to a water storage with a constant head (900 mm). The drain was kept closed for 24 hours to let the samples become completely saturated. Then the drain tap was opened to let the water move through the sample (Figure 2). Normal tap water was used in the leaching process. The pore water composition has a significant effect on the porosity. Based on the previous research, the void ratio of samples which were leached with saline water was about twice as the ones leached with distilled water. This is mainly due to the high concentration of Na^+ and Cl^- ions effect on the solubility of calcium sulfate. As the time passes, the amount and the rate of calcium sulfate solubility and consequently the concentration of Na^+ and Cl^- ions in pore water increases. Due to the presence of chlorine in tap water, leaching is significantly higher with more calcium sulfate solubility compared to leaching with distilled water (Azam *et al.*, 1998).

For each sample, every 150 ml of the leaked water was gathered and used to measure TDS, chlorine, CH and pH. Between each water gathering stage, the drain tap was kept closed for 1 to 2 hours to let the salts concentration balance (Ismael & Mollah, 1998). Leaching was continued until the TDS, chlorine, and CH reached a constant value. At the end of leaching, there were still some salts in the samples which were not readily soluble in freshwater and needed specific chemical additives to be solved. Since the objective of this research was to simulate a natural leaching situation, no effort was made to solve the remaining salts. It was proven that the leaching of a significant portion of SO_4^{2-} and Ca^{2+} ions happens in the first stages of the test. This prevents the calcium sulfate to show its complete volume change. The penetration of fluids and leaching of SO_4^{2-} and Ca^{2+} ions breaks the crystal bonds of gypsum. The concentration of Ca^{2+} ion is always higher than of SO_4^{2-} and as a result, several large void spaces remain in the soil (Azam *et al.*, 1998).



Figure 2: The cell used for soil leaching (left) and sample G2 after leaching (right)

Chemical analysis results of all water samples including minimum, average and maximum TDS, Cl⁻, CH and pH are summarized in Table 3. The changes in TDS, CH and Cl⁻ in time are also plotted in Figures 3 to 8. As the table and graphs depict, in the initial stages of leaching, samples have large quantities of gypsum, TDS has its maximum value and Cl⁻ and CH are increasing. As the leaching continues, all of these 3 parameters decrease and tend to a constant value.

Table 3: The chemical analysis results of all water samples

Sample	TDS Max (mg/ml)	TDS Min (mg/ml)	TDS Mean (mg/ml)	Cl ⁻ Max (ppm)	Cl ⁻ Min (ppm)	Cl ⁻ Mean (ppm)	CH Max (ppm)	CH Min (ppm)	CH Mean (ppm)	pH Max	pH Min	pH Mean
G1	1500	1310	1405.0	7.36	4.39	5.74	272	157	214.50	6.00	7.30	6.65
G2	3000	1200	2100.0	17.95	6.04	11.99	395	239	317.00	7.30	8.40	7.85
G3	1344	1260	1302.0	9.31	3.78	6.54	399	99	249.00	7.17	8.20	7.68
G4	1390	1200	1295.0	6.80	4.50	5.65	194	70	132.00	7.30	7.80	7.55
G5	1310	1198	1254.0	8.88	4.68	6.78	220	159	189.50	6.64	7.90	7.27
G6	2330	1321	1825.5	9.80	3.48	6.64	224	107	165.50	7.00	7.80	7.40
G7	1270	1181	1225.5	8.99	4.38	6.68	260	130	1950.0	7.10	8.00	7.55

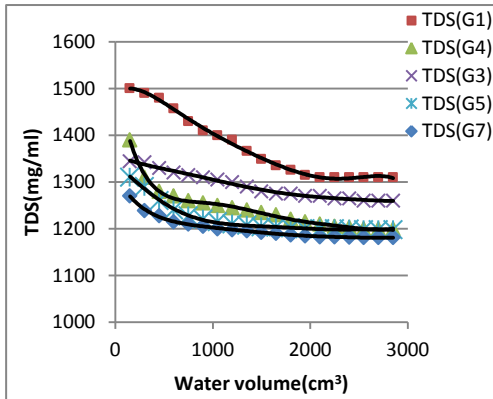


Figure 3: The changes in TDS for all samples

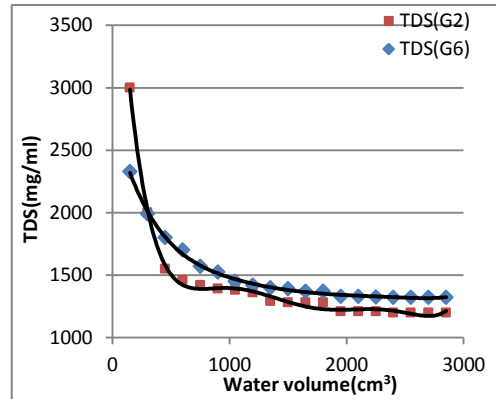


Figure 4: The changes in TDS for G2 and G6 samples

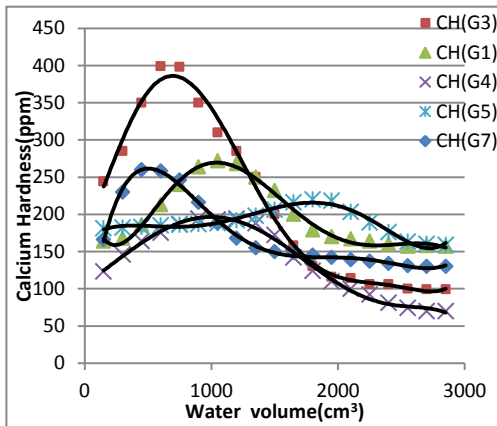


Figure 5: The changes in CH for all samples

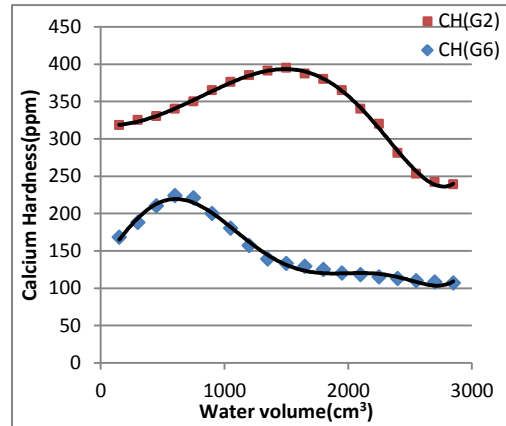
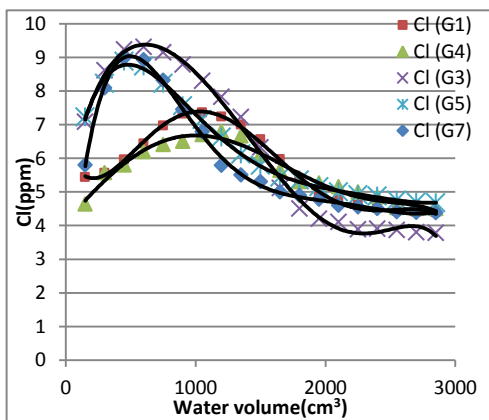
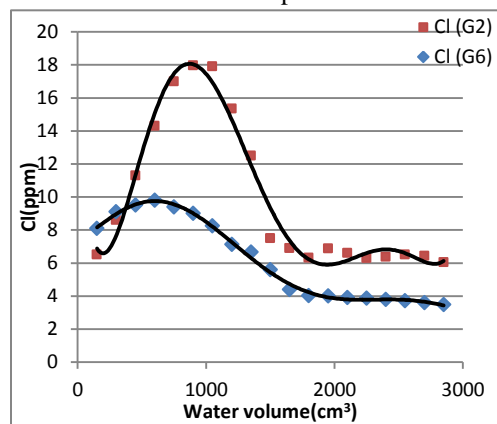


Figure 6: The changes in CH for G2 and G6 samples

Figure 7: The changes in Cl⁻ for all samplesFigure 8: The changes in Cl⁻ for G2 and G6 samples

3.3 Hydraulic Tests

Permeability test was conducted on the samples and the summary of the results as maximum, minimum and mean hydraulic conductivity (K) is presented in Table 4. K changes in time were plotted in Figures 9 and 10. As depicted in these figures, in samples with the highest amount of gypsum (G2 and G6), hydraulic conductivity was initially high and then rapidly decreased. Several reasons are proposed for this rapid decline in leakage. For instance, in the beginning of saturation, this decline was due to the changes in the transferred ions ratio and dispersion of the particles and then due to the weakening bonds in cementation, collapse of the soil particles and subsidence under static load (Nejadhashemi *et al.*, 2000). Moreover, the amount of decline in samples with low permeability coefficient was lower and the constant state was reached faster. In samples with higher permeability coefficient (G2 and G6) on the other hand, reaching the constant state was lengthier. This might be due to two reasons:

- a. The movement of air bubbles in micro joints (this is probably more important in the samples with high permeability)
- b. Increase in the thickness of absorbed water layer around cementing particles which makes the cement harder and prevent it from expansion (Jackson, 1974).

In the samples with lower gypsum content (G1, G3, G4, G5, G7), after a small initial increase, the permeability coefficient tends to a constant value. Our results were similar to Nejadhashemi *et al.* (2000) research which showed that the leakage capacity of gypseous soils increases in the initial stages of leaching and then decreases and tends to a constant value. This might be due to two reasons:

- a. The small initial increase in the permeability coefficient might be due to the increase in the saturation level of samples.
- b. The increase of permeability in the unleached samples is related to continuous expansion and the formation of new micro joints (Jackson, 1974).

Table 4: Maximum, minimum and mean hydraulic conductivities (K)

Sample	K Max (cm/s)	K Min (cm/s)	K Mean (cm/s)
G1	3.34E-05	2.89E-05	3.11E-05
G2	2.00 E-04	1.06E-04	1.53E-04
G3	8.76E-05	7.53E-05	8.14E-05
G4	1.06E-04	9.34E-05	9.98E-05
G5	4.48E-05	4.32E-05	4.40E-05
G6	4.70E-04	1.90E-04	3.30E-04
G7	5.26E-05	4.71E-05	4.99E-05

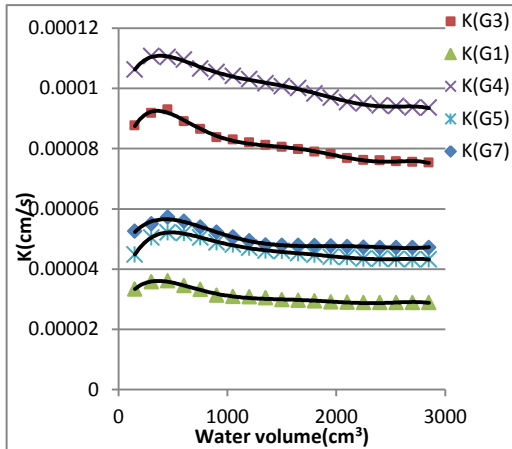


Figure 9: The changes in K for all samples

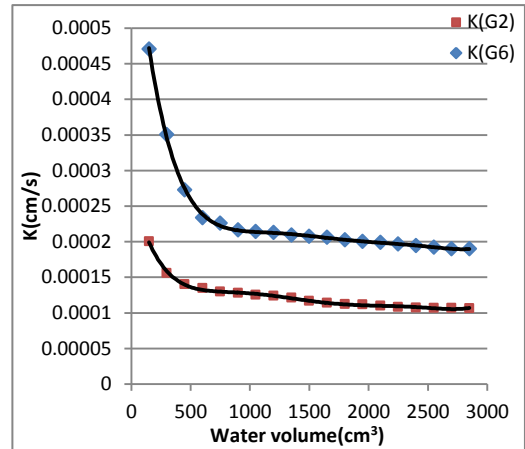


Figure 10: The changes in K for G2 and G6 samples

3.4. Determination of Depth of Maximum Gypsum and Sulfate Concentration

Previous studies in the area did not estimate the maximum depth of gypsum concentration. To determine this depth, data from chemical tests on samples taken from 511 boreholes in the area and the data available from several available sources were used. Statistical analysis on the data showed that the maximum concentration of gypsum was from 0 to 4 meters depth, which is due to the leaching of gypsum and its concentration in this depth. Figure 11 shows the statistical distribution of gypsum and sulfate concentrations in different depths.

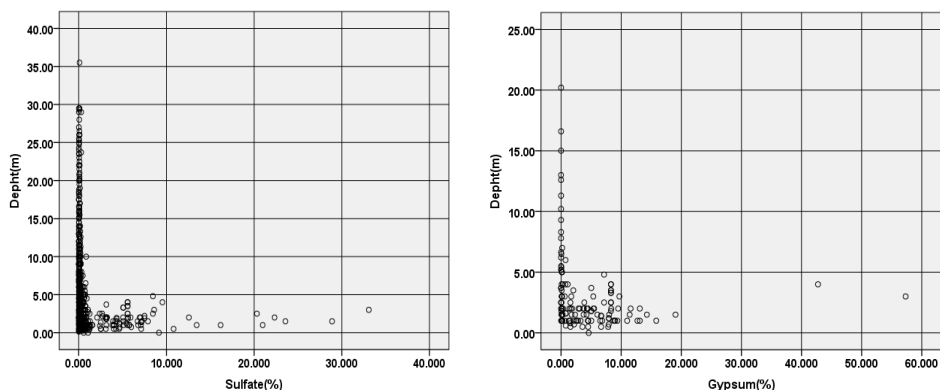


Figure 11. The statistical distribution of gypsum (left) and sulfate (right) concentrations in different depths in the area.

5.0 Conclusions

In the initial phase of leaching when the samples had large amount of gypsum, TDS was maximum and the concentration of chlorine and calcium were increased. As the leaching progressed, all three parameter decreased and tend to a constant value.

1. Since after 5 days of leaching with constant head, there were still traces of gypsum in the samples, we concluded that the collapse in gypseous soils was not due to the removal of gypsum but rather was a result of softening or disruption of gypsum bonds between soil particles.
2. The permeability coefficient of gypseous soils in the first stages of leaching was high due to the dispersion and movement of particles but gradually decreased and tends to a constant value.
3. Since gypsum cannot be removed easily, saturation of gypseous soils is not sufficient to mitigate additional subsidence in engineering projects. Thus it is recommended to keep water away from these soils.
4. Based on statistical analysis, the maximum concentration of gypsum is in 0 to 4 meters depths which are attributed to the leaching of gypsum from the surface and its concentration in this depth.

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