



Erosion Studies on Lithomargic Clays

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Abstract Lithomargic clays are found at shallow depths in lateritic formations, sandwiched between hard lateritic crust at top and the parent granitic gneiss underneath. Many earlier studies have proved that the behaviour of these soils is similar to dispersive soils, and they are also found to be highly erosive. Very few and detailed studies on erosion of lithomargic clays are available in the literature. Lithomargic clays along the western coastal belt of peninsular India are available with varying percentages of sands and fines (especially silts, with negligible amount of clays occasionally). In this study, a number of hole erosion tests are conducted on controlled lithomargic clay samples with varying percentage of fines to study their erosion characteristics. The influence of degree of compaction, moulding water content, head causing flow, percentage silt content and plasticity index on the erosion rate index and critical shear stress of controlled lithomargic clay samples are being studied. The results of this study indicate that the critical shear stress for soils with higher silt fraction and fine sand content varied from 45 to 125 N/m², whereas for soils with higher clay fraction and fine sand content the critical shear stress varied from 200 to 400 N/m². The

erosion rate increased with a decrease in percentage compaction in all the samples, and critical shear stress is found to be highest at optimum moisture content conditions. It is generally observed that soils with fines whose plasticity indices are high, are less erodible compared to soils with fines whose plasticity indices are low.

Keywords Lithomargic clay · Erosion · Hole erosion test · Erosion rate index · Critical shear stress

Introduction

The study area, along western coast of peninsular India, has abundance of lateritic formations comprising of hard laterite at top, underlain by lithomargic clay, underlain by parent rock. Lithomargic clays are products of laterization or tropical weathering. In most cases, top laterites are quarried for use as bricks in construction in this area, exposing the underlying lithomargic clay. Therefore, soils in the study area are typically combinations of one or more of the following: lateritic soils (crushed and powdered laterites), lithomargic laterites (with small percentage of lithomargic clay), lateritic lithomarges (with higher percentage of lithomargic clay) and lithomargic clays (no laterites).

Lithomargic clays, predominantly comprising of fine sand and silt fraction, are a problematic soil since they lose much of their strength when they come in contact with water and behave similar to dispersive soils. Apart from loss of strength of lithomargic clays due to saturation, erosion (both internal erosion and external erosion) has also contributed to instability of slopes in the region. Slope and embankment failures in lithomargic soils, especially during monsoon season, have caused enormous economic

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losses. Various stabilization techniques using cement, quarry dust, GBFS, lime, sand and coir [1–4] have been adopted with lithomargic clays to enhance their strength behaviour. SEM and XRD studies [5], electrical resistivity studies [6] have also been conducted on stabilized lithomargic clays. Very few research studies have been reported on the erosion characteristics of lithomargic clay and its impact on stability of excavated slopes in lateritic formations.

Erosion, over a period of time, leads to geometric changes of slope with subsequent major distress finally causing failure. Erosion can be categorized into surface erosion caused by running water on slope surface and internal erosion occurring within the structure. Internal erosion is the result of a coupled process of surface erosion from the interior of the soils and the subsequent fate of eroded particles in the pores [7]. Various qualitative and quantitative studies have been conducted to measure the erosion characteristics of soils. Sherard et al. [8] developed the pinhole test to directly measure the dispersibility of compacted fine-grained soils in which water is allowed to flow through a small hole of 1 mm diameter in a soil specimen to stimulate water flow through a crack or other concentrated leakage path in the impervious core of a dam or other structure. Lewis and Schmidt [9] conducted an investigation to determine the influence of dry density and initial water on the erosion of compacted dispersive clay using the pinhole test. Wan and Fell [10–12] extended pin hole test [13] into a quantitative method for measuring internal erosion, called the hole erosion test (HET), by measuring changes in flow rate with time to back-calculate changes in the pipe diameter and thus the internal erosion [14].

The hole erosion test (HET) developed by Wan and Fell [10–12] is one of several available methods for quantifying the erosion characteristics of soils. The eroding fluid is passed through a hole of 6 mm diameter predrilled along the longitudinal axis of the soil sample, simulating the piping erosion occurring in embankment dams. Hole erosion test [15–19] is one of the convenient and efficient erosion tests which are normally carried out to study the piping erosion in soils with fines. The erosion characteristics are described by the erosion rate index, which measures the erosion rate and the critical shear stress, which represents the minimum shear stress required to start progressive erosion. The rate of erosion is shown to be dependent on the soil fines and clay-sized content, plasticity and dispersivity; compaction, water content, density and degree of saturation; and clay mineralogy, and possibly the presence of cementing materials such as iron oxides [11]. Lim [20] conducted hole erosion tests to study the study the erosion behaviour of clay soils. Dispersive erosion which is indicated by murky or cloudy outflow is

characterized by instantaneous erosion and quick enlargement of the hole, inferring substantial erosion at small shear stress. The erosion is mainly induced by the dispersive nature or by slaking in unsaturated cohesive soils. Slaking is due to excess air pressure in the capillaries because of surface tension force in partially saturated soil. The pressure exerted by the entrapped air in the pores breaks loose small bits of soil on the surface [21]. Coarse-grained, non-cohesive soils, in general, erode more rapidly and have lower critical shear stresses than fine-grained soils. Hole erosion tests were conducted on silty sand and clay stabilized with lignosulphonate and cement [22]. A linear variation of erosion rate with the hydraulic shear stress was observed for treated and untreated soil samples compacted at 95% and 90% of the maximum dry density. The effect of compaction energy, moisture content, degree of saturation, and the percentage of fines on critical shear stress and coefficient of erosion for different types of kaolinite has also been studied by conducting HET [23]. Knowledge of the erosion characteristics of the soil in the core of an embankment dam aids in the evaluation of the possibility of dam failure due to piping erosion.

Lithomargic clays are locally called as ‘shedi soils’. There are serious problems of erosion of shedi soils in slopes during heavy rainfall since the shedi soils are highly erosive and dispersive by nature. Due to the highly erosive nature of the lithomargic clays, in excavated slopes, especially for highway or railway purposes, caving in or scouring of the lithomargic layers in excavated slopes is a common sight along NH 66 and along Konkan rail route, right from Trivandrum in the south to Mumbai in the north. Excavated slopes for railway and highway projects in such lateritic formations pose serious erosion and slope stability problems [24], especially, due to the presence of these shedi soils and seepage pressures from stagnated water at the top.

In this paper, the influence of various parameters, such as degree of compaction, moulding water content, head causing flow, percentage silt content, plasticity index, on the internal erosion characteristics of lithomargic clay are carried out by conducting hole erosion tests.

Experimental Investigation

In the present study, hole erosion tests have been conducted to study the erosion characteristics of the lithomargic clay and their erosion potential. The various factors influencing erosion such as water content, degree of compaction and head causing flow, are being studied.

Materials Used

Two lithomargic clay samples were procured from two nearby sites from depths of 2–3 m below ground level, below the laterite layers. These lithomargic clay samples had particle sizes finer than 150 μ sieve size. The first procured sample (designated as C0 sample) had higher percentage of clay fraction (smaller than 2 μ size) {55.3%}, and second procured sample (designated as M0 sample) had higher percentage of silt fraction (2 μ to 75 μ size) {79.9%}. Both these samples were blended in the laboratory with different percentages (10%, 20%, 30% and 40%) of river sand (passing 1.18 mm sieve) to prepare controlled samples. These samples are designated as C10, C20, C30, C40 (for C0 blended samples) and as M10, M20, M30, M40 (for M0 blended samples), respectively. C samples are soils with higher percentage of clay fraction (or high compressibility soils with liquid limit in excess of 50%), and M samples are soils with higher percentage of silt fraction (or liquid limit less than 50%). Controlled soil samples thus prepared were then studied for both geotechnical and erosion properties.

Samples Tested

A series of hole erosion tests are carried out on all the ten samples at various water contents (namely at 50% of OMC, at OMC and at full saturation), hole diameters (6 mm and 8 mm) and compaction (100%, 90% and 80%) with the suitable range of head (within the laboratory constraints). The basic geotechnical properties of all the C and M soil samples are listed in Table 1 and Table 2, respectively.

Hole Erosion Test (HET)

Experimental Setup

The schematic diagram of the experimental setup used for the hole erosion tests is shown in Fig. 1. It consists of a constant head tank, an inlet chamber, the mould along with the specimen, an overflow container, a collecting tank and a weighing balance. The constant head upstream tank is provided with a continuous water supply. The inlet chamber is connected to the constant head tank. It is filled with 20 mm coarse aggregates to reduce the impact of water on the soil specimen. An air valve is provided in the inlet chamber to remove air bubbles (if any) during the experiment. The plate in between the inlet chamber and the specimen is provided with a hole of diameter 5 cm to ensure uninterrupted flow of water through the specimen. A wire mesh is fixed on the plate to avoid the coarse aggregates from disturbing the specimen. The hole erosion test apparatus is shown in Fig. 2.

The weight of the overflowing water is continuously measured. The discharge at various time intervals was calculated from the weight, and the head was obtained by measuring the vertical distance between the water level in the overhead tank and the free water surface at the downstream end. The test is terminated (by closing the downstream valve) upon observing one of the following conditions (i) several minutes of accelerating flow, no significant erosion in one hour at maximum test head, (ii) extreme erosion with hole enlargement, reaching the walls of the mould [25].

Table 1 Geotechnical properties of C samples

Parameter	C0	C10	C20	C30	C40
Specific gravity (G)	2.56	2.57	2.61	2.63	2.65
Maximum dry density (γ_{dmax}) (kN/m ³)	14.22	14.32	14.81	15.70	15.99
Optimum moisture content (OMC) (%)	27.0	26.4	24.3	23.0	19.6
Void ratio (at γ_{dmax})	0.77	0.76	0.73	0.64	0.63
Plastic limit (%)	30.0	29.0	26.0	25.0	24.0
Liquid limit (%)	53.0	50.0	45.0	41.0	39.0
Plasticity index (PI)	23.0	21.0	19.0	16.0	15.0
Fine fraction (dusty fraction)					
Clay fraction (%) (< 2 μ)	55.3	49.8	44.2	38.7	33.2
Silt fraction (%) (2 μ to 75 μ)	42.7	38.4	34.2	30.7	26.3
Coarse fraction					
Sand fraction (%) (75 μ to 4.75 mm)	2.0	11.8	21.6	30.6	40.5
Gravel fraction (%) (> 4.75 mm)	0.0	0.0	0.0	0.0	0.0
Unified soil classification	MH	MI-MH (boundary classification)	CI	CI	CI

Table 2 Geotechnical properties of M samples

Parameter	M0	M10	M20	M30	M40
Specific gravity (G)	2.49	2.50	2.52	2.54	2.58
Maximum dry density (γ_{dmax}) (kN/m ³)	13.24	14.03	15.21	15.40	16.58
Optimum moisture content (OMC) (%)	27.2	24.6	20.2	18.8	16.4
Void ratio (at γ_{dmax})	0.81	0.76	0.63	0.61	0.53
Plastic limit (%)	36.0	31.0	25.0	23.0	22.0
Liquid limit (%)	48.0	46.0	41.0	36.0	31.0
Plasticity index (PI)	12.0	15.0	16.0	13.0	9.0
Fine fraction (dusty fraction)					
Clay fraction (%) (< 2 μ)	16.6	13.3	13.2	12.3	7.4
Silt fraction (%) (2 μ to 75 μ)	79.9	74.5	64.1	55.1	51.0
Coarse fraction					
Sand fraction (%) (75 μ to 4.75 mm)	3.5	12.2	22.7	32.6	41.6
Gravel fraction (%) (> 4.75 mm)	0.0	0.0	0.0	0.0	0.0
Unified soil classification	MI	MI	CI	CI	CL

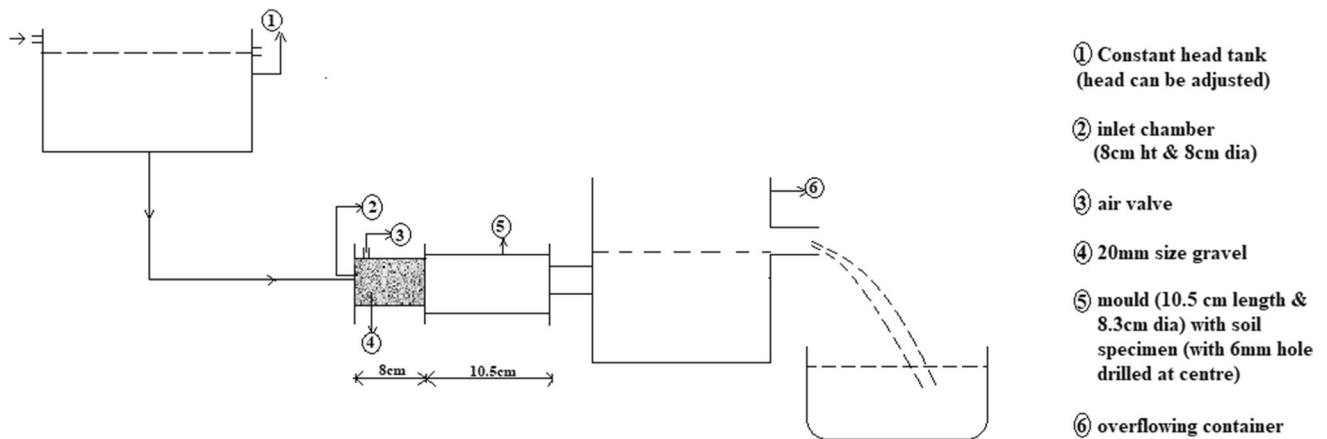


Fig. 1 Schematic diagram of the hole erosion test setup

Fig. 2 Hole erosion test apparatus (without constant head tank)



Specimen Preparation

The test specimens were prepared at the required dry density and water content. The soils were compacted to a

thickness of 105 mm in a mould of 83 mm diameter corresponding to the desired dry density. The samples were then kept in a desiccator for 1 day. This was to attain uniform moisture content throughout the sample.

Test Procedure

A hole of 6 mm diameter was drilled along the central longitudinal axis of the specimen. The two circular surfaces of the specimen were coated with paraffin excluding an inner circular area of 3 cm around the hole. This is done to avoid the dispersion of the soil surface. The inlet chamber is filled with 20-mm gravels in order to regulate the flow of water on the upstream side of the sample and also to reduce the impact of water on the specimen surface. The soil sample is placed between the inlet chamber and overflow container. It is ensured that a constant head is maintained throughout the test. When the inlet valves are opened, the air bubbles are eliminated by opening the air valve provided at the inlet chamber. The flow rate at the downstream side of the apparatus was measured at different time intervals during the test. The final hole diameter is noted after the test.

Equations Governing Hole Erosion Test

Wan and Fell [10–12] developed the hole erosion test to measure the erosion properties of soils. The rate of erosion per unit surface area of the hole is expressed in Eq. 1.

$$\varepsilon_t = C_e(\tau_t - \tau_c) \tag{1}$$

where ε_t is the rate of erosion per unit surface area of the hole at time t (kg/s/m²); C_e is a constant known as the coefficient of soil erosion (s/m); τ_t is the hydraulic shear stress along the hole at time t (N/m²); τ_c is the critical shear stress, i.e. the minimum shear stress required to initiate progressive erosion (N/m²).

The hole diameter at any time during erosion is calculated by Eqs. 2 and 3 for laminar and turbulent flow, respectively.

$$\phi_t = \left(\frac{16Qf_L}{\pi\rho_wgs} \right)^{\frac{1}{5}}, \text{ for laminar flow conditions} \tag{2}$$

$$\phi_t = \left(\frac{16Q^2f_T}{\pi^2\rho_wgs} \right)^{\frac{1}{5}}, \text{ for turbulent flow conditions} \tag{3}$$

where ϕ_t (m) is the hole diameter at time t ; Q (m³/s) is the flow rate through the hole at time t ; f_L and f_T are the friction factors for laminar and turbulent flow conditions; g (m/s²) is the acceleration due to gravity; s is the hydraulic gradient across the hole at time t ; and ρ_w (kg/m³) is the density of the eroding fluid. The erosion rate and hydraulic shear stress were then calculated using Eqs. 4 and 5, respectively.

$$\varepsilon_t = \frac{\rho_d}{2} \left(\frac{d\phi_t}{dt} \right) \tag{4}$$

$$\tau_t = \frac{\rho_wgs\phi_t}{4} \tag{5}$$

where ε_t (kg/s/m²) is the erosion rate; ρ_d (kg/m³) is the dry density of the soil. According to Wan and Fell [10–12], the erosion rate changed linearly with the hydraulic shear stress. The coefficient of soil erosion C_e is the slope of the straight line obtained from plotting ε_t against τ_t . The critical shear stress, τ_c , can be obtained graphically by extrapolating the plot of ε_t versus τ_t to zero.

The rate of erosion of a soil can be represented by an ‘erosion rate index’ ‘ I_h ’ which can be derived from the results of the hole erosion test as:

$$I_h = -\log(C_e) \tag{6}$$

The rate of progression of erosion is classified as per Table 3. Soils that erode rapidly have lower I_h values than soils that erode slowly.

Hole Erosion Test Results

Determination of Critical Head

Test results indicated slaking for C samples (clay fraction 33.2–55.3%, silt fraction 26.3–42.7%, PI 15–23%) when tested at various heads ranging from 50 to 100 cm. Slaking by definition is the ‘disintegration of unconfined soil after exposure to air and subsequent immersion in water; no external confining pressure is assumed to act over the soil prior to immersion’ [26]. However, all the C samples underwent progressive erosion from a head of 110 cm. Tests were conducted on C specimens at heads of 110 cm, 125 cm, 140 cm and 155 cm. In contrast, all the M samples (clay fraction 7.4–16.6%, silt fraction 51.0–79.9%, PI 9–16%) underwent progressive erosion from a head of 30 cm. Tests were conducted on M specimens at heads of 30 cm, 40 cm, 60 cm and 70 cm. At higher heads, the

Table 3 Qualitative relation of representative erosion rate index and progression of internal erosion as recommended by Wan and Fell [10–12]

Group number	Erosion rate index ($I_h = -\log(C_e)$)	Progression of internal erosion
1	< 2	Extremely rapid
2	2–3	Very rapid
3	3–4	Moderately rapid
4	4–5	Moderately slow
5	5–6	Very slow
6	> 6	Extremely slow

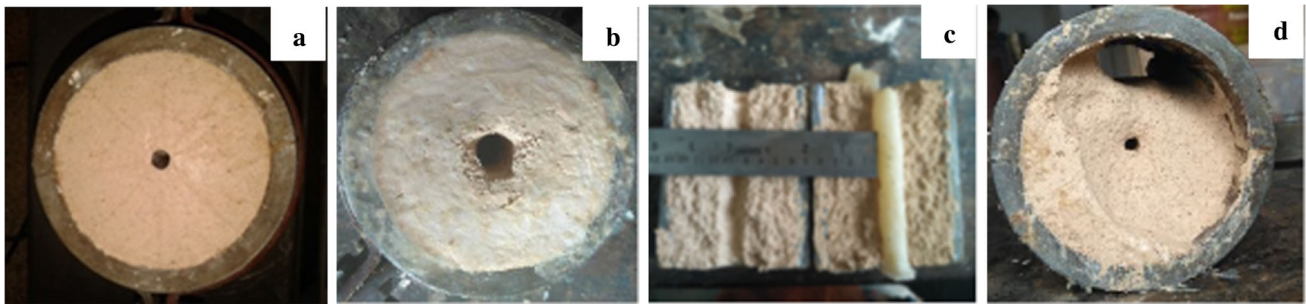


Fig. 3 a Sample before test with 6-mm hole, b Sample (C10) which showed very less surface erosion after HET when coated with wax on its surface, c cross section of a sample after HET, d formation of second hole due to slaking

Fig. 4 a Variation of discharge with time, b evolution of hole diameter over time; for C40 sample

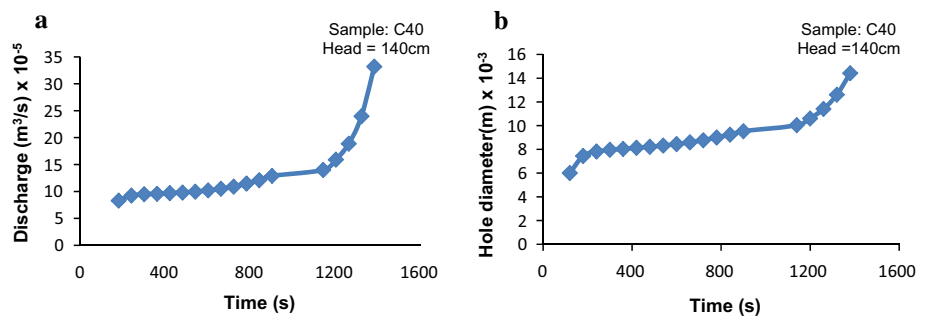
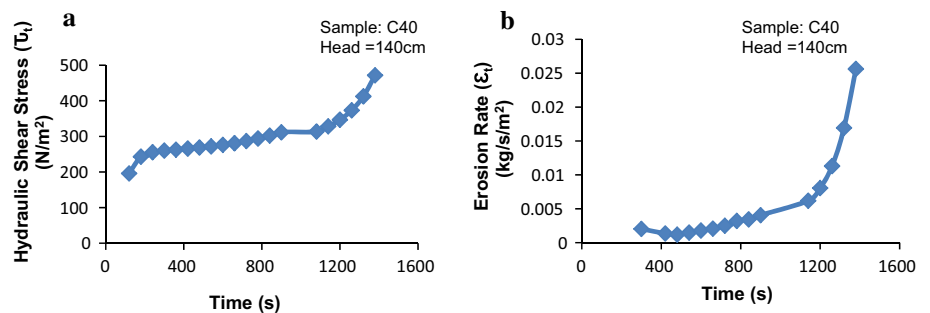


Fig. 5 Variation of a hydraulic shear stress, b erosion rate; with time for C40 sample under a head of 140 cm



specimens were washed off. The soil samples at different stages or conditions of HET are shown in Fig. 3a–d.

Typical Results (Determination of I_h and C_e)

The discharge (Fig. 4a), hole diameter (Fig. 4b), hydraulic shear stress (Fig. 5a) and erosion rate (Fig. 5b) were plotted with time. The erosion rate was plotted against hydraulic shear stress (Fig. 6) to know whether progressive erosion has occurred and also to understand how critical the erosion is.

The typical results obtained for progressive erosion are shown in Figs. 4, 5 and 6. The variation of discharge with time showed that the discharge increased from 0.0001 to 0.00033 m³/s (Fig. 4a). The evolution of hole diameter over time indicates that hole diameter increased from 6 to

15 mm in 24 min (Fig. 4b). It is important to note that the hole diameters represented average diameters as they varied over the length. The hole was enlarged at both ends. This is due to the spalling of soil caused by eddies present in the inlet and outlet [27]. In some cases, surface had been eroded reducing the length of the eroded hole.

The hydraulic shear stress increased over time from 150 to 475 Pa over a time of about 24 min (Fig. 5a). The rate of increase in hydraulic shear stress increased towards the end of the test. The increase in rate of erosion represents the rate of increase in hole diameter over time. Figure 5b indicates that progressive erosion has occurred during the test. A slightly decreasing trend observed initially represents the clean off phase, where the loose soil particles around the hole are removed by water and is called as cleanout erosion. These are formed due to the disturbances

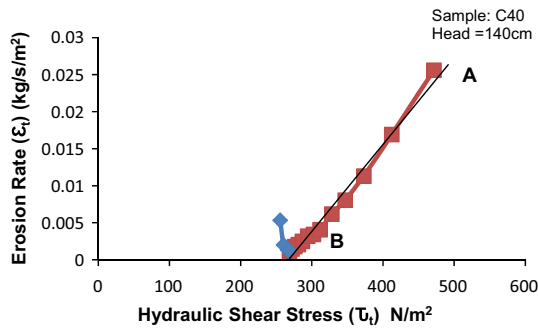


Fig. 6 Plot of erosion rate v/s hydraulic shear stress

caused in the sample, while the hole is being drilled. The hole stabilizes itself during the cleanout erosion and when the critical shear stress is attained progressive erosion is initiated.

Figure 6 shows a plot of erosion rate [ϵ_t (kg/s/m^2)] versus hydraulic shear stress [τ_t (N/m^2)] for sample C40. Therein, AB represents the best fit curve of the increasing portion of erosion rate v/s shear stress relationship. Its slope gives the coefficient of soil erosion (C_e), and the hole erosion index (I_h) is obtained as 4.52 for the sample C40 under a head of 140 cm. As per the soil classification by Wan and Fell [10–12], the erosion rate of soil may be classified as moderately slow (Table 3). The intercept of the best fit line with the x -axis gives the critical shear stress and is obtained as 270 N/m^2 (Fig. 6). This value is less than the critical shear stress obtained for other samples containing lesser sand fraction.

Influence of Change in Moulding Water Content

In excavated slopes, in lateritic formations, caving in of lithomargic clay soil can be observed after heavy rainfall. After a first few days of constant and low intensity rainfall, the soil gets fully saturated causing erosion of lithomargic clay. After a heavy intensity rainfall (higher heads due to stagnation), wash off might occur, resulting in caving in or concavities. These conditions were simulated in the laboratory by varying the moulding water content of the soil and by applying varying heads of water. Specimens were prepared with the different fines and sand combinations at varying water contents. The soils were compacted to their maximum dry densities.

C Samples

Three water contents used were such as the optimum moisture content (OMC) of the corresponding samples, 50% of optimum moisture content and the water content corresponding to 100% saturation (i.e. 110% of optimum moisture content). This is done to study the influence of

moulding water content on erosion index (I_h) of C samples. The samples were tested at heads of 110 cm, 125 cm, 140 cm and 155 cm.

(i) Soil Samples ('C' Samples) Prepared at 50% OMC

The soil samples were compacted to maximum dry density at a moisture content corresponding to 50% of OMC. The observations for C samples are shown in Fig. 7a, b. The erosion rate index of all the soil samples varies from 3.95 to 4.76. Hence, the rate of erosion may be classified as moderately slow according to Wan and Fell [10–12] as shown in Table 3. An increase in erosion rate index represents a decrease in the rate of erosion. From Fig. 7a, it can be observed that the original lithomargic clay sample C0 has the maximum rate of erosion and sample C40 (in which lithomargic soil C0 was mixed with 40% river sand) is having least erosion rate and therefore is more stable. When the sample is compacted at 50% OMC the eroding water has to seep radially through the sample to wet the soil and disperse it. Hence, the soil containing the highest void ratio allows water to pass more easily through it. C0 has the highest void ratio and hence is the most erodible, while C40 has the least void ratio. In addition, the sand fraction in the C40 sample adds stability to the soil structure. The rate of wetting is higher when the velocity of water is the least. Hence, a higher rate of erosion is observed at lower heads. To confirm the same, UCC samples were prepared and immersed in water and the time taken by the soil samples to fully disperse was determined. It was found that the C0 sample dispersed more quickly than C40 sample.

(ii) Soil Samples ('C' Samples) Prepared at OMC

The soil samples were compacted to maximum dry density with a moisture content corresponding to their OMC. The erosion rate index varied from 3.89 to 4.84 in case of samples moulded at OMC (Fig. 8a). The C40 sample is seen to be more stable than C0 sample. The soil is not fully saturated at OMC and the better soil size distribution of C40 sample makes it more resistant to erosion. The water passing through the hole removes the soil surrounding it. The non-eroded portion of the sample remains undisturbed after the test and no significant change in the water content has been noticed. As the head increases, the stress acting on the soil increases and consequently erosion rate increases. The variation of coefficient of soil erosion, C_e , of various samples compacted at OMC for C samples is shown in Fig. 8b.

(iii) Soil Samples ('C' Samples) Prepared at 110% OMC (fully saturated condition)

The samples were compacted to maximum dry densities at water content corresponding to 110% of OMC (fully

Fig. 7 Variation of **a** erosion rate index (I_h), **b** coefficient of soil erosion, C_e , of C samples compacted at 50% of OMC

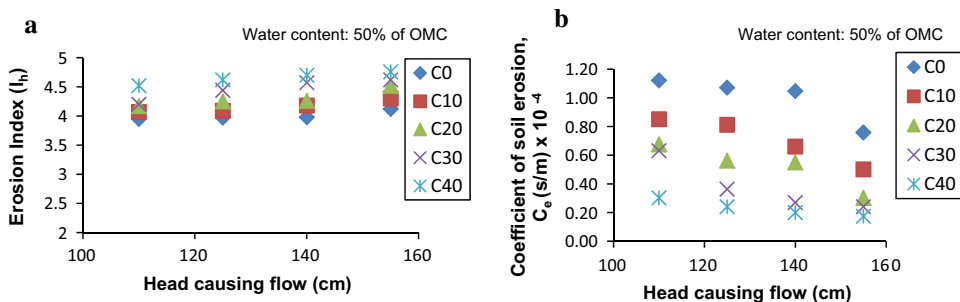
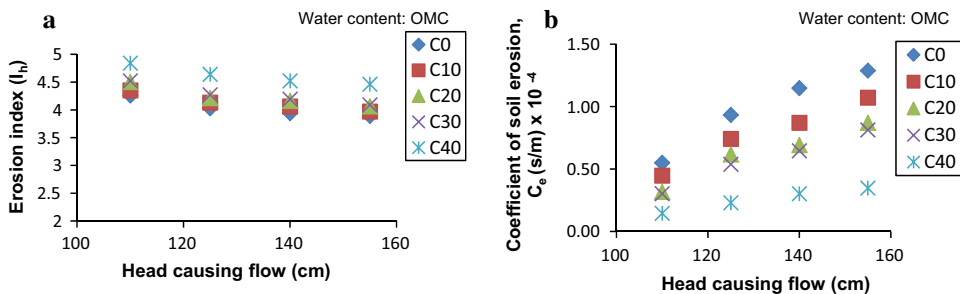


Fig. 8 Variation of **a** erosion rate index (I_h), **b** coefficient of soil erosion, C_e , of C samples compacted at OMC



saturated condition), and the erosion rate index varied from 3.67 to 4.64. When fully saturated, C0 sample which had more cohesion due to high percentage of fine fraction of soils was more stable (Fig. 9a, b). In C0 sample, it was observed that the fines eroded as individual particles and not as lumps. At higher heads, samples containing higher sand content were washed off. The sand soil mix was found to be deposited in the overflowing jar as lumps. Also as the head increases the rate of erosion increased due to the increase in hydraulic shear stress.

M samples

Three various water contents used were such as the optimum moisture content (OMC) of the corresponding samples, 50% of optimum moisture content and the water content corresponding to 100% saturation (106% of optimum moisture content). This is done to study the influence of moulding water content on erosion index (I_h) of M

samples. The samples were tested at heads of 30 cm, 40 cm, 60 cm and 70 cm.

(i) Soil Samples ('M' Samples) Prepared at 50% OMC

The soil samples were prepared at maximum dry density at a moisture content corresponding to 50% of OMC. The erosion rate index varies from 2.77 to 3.7 (Fig. 10a) and can be classified as very rapid to moderately rapid erosion (Table 3). It can be observed that the M40 sample (M0 sample + 40% sand) has lower I_h value and thus has the maximum rate of erosion. The original lithomargic soil sample (sample M0) has higher I_h value and so is the most stable. The M0 sample is more stable because of higher percentage of fines (because of which it possesses higher cohesion) and lesser sand fraction. The cohesion in the M0 sample acts as a bond and holds the soil particles together. Due to the higher percentage of sand along with silt content in the M40 sample, the cohesion is less and it gets eroded more and hence is least stable. The erosion also increases with head causing flow. Higher rate of erosion is observed

Fig. 9 Variation of **a** erosion rate index (I_h), **b** coefficient of soil erosion, C_e , of C samples at fully saturated condition (Note: W denotes wash off occurred beyond this head)

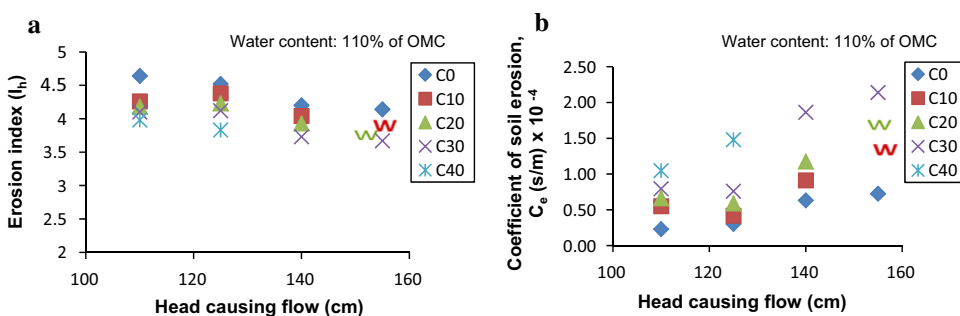
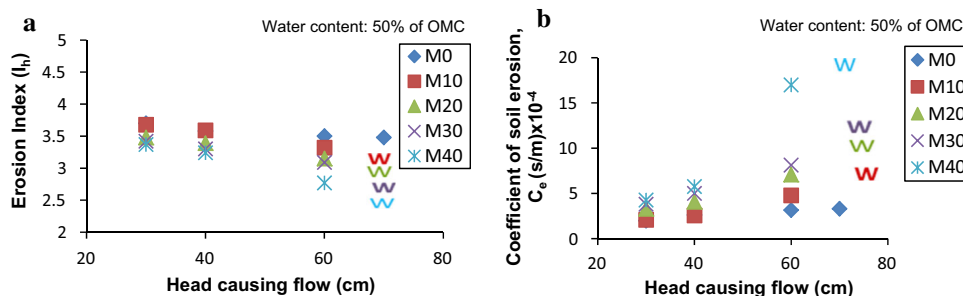


Fig. 10 Variation of **a** erosion rate index (I_h), **b** coefficient of soil erosion, C_e , of M samples compacted at 50% of OMC (Note: W denotes wash off occurred beyond this head)



at higher heads. The variation of coefficient of soil erosion, C_e , of various samples compacted at 50% OMC is shown in Fig. 10b.

(ii) Soil Samples (‘M’ Samples) Prepared at OMC

The soil samples were compacted to maximum dry density with a moisture content corresponding to their OMC. The erosion rate index varies from 2.96 to 3.69 (Fig. 11a) and can be classified as moderately rapid erosion as per Table 3. At OMC conditions, M0 sample had maximum cohesion due to the increase in water content and hence was more stable. As the head increases, the stress acting on the soil increases, and consequently, erosion rate increases. The variation of coefficient of soil erosion, C_e , of M samples compacted at OMC is shown in Fig. 11b.

(iii) Soil Samples (‘M’ Samples) Prepared at 106% OMC (fully saturated condition)

The soil samples were prepared at maximum dry density at a moisture content corresponding to 106% of OMC (fully saturated condition). The erosion rate index varies from 2.59 to 3.35 (Fig. 12a). Hence, the rate of erosion may be classified as very rapid to moderately rapid as per Table 3. A decrease in the erosion rate index represents an increase in the rate of erosion. At 106% of OMC, M0 sample had fullest cohesion due to the highest degree of saturation and hence was more stable. As the head increases, the stress acting on the soil increases, and consequently, erosion rate increases. The variation of

coefficient of soil erosion, C_e , of M samples compacted at OMC is shown in Fig. 12b.

It can be inferred that erosion is higher at full saturation and lower at partially saturated condition including at OMC. As fine sand fraction increases, erosion also increases.

Influence of Degree of Compaction

C Samples

To understand the influence of degree of compaction, hole erosion tests were conducted on C20, C30 and C40 samples. Soil samples were compacted to 80%, 90% and 100% of their maximum dry densities. The water contents were the corresponding moisture content on light compaction curves on the dry side of optimum. Specimens were tested at heads of 125 cm, 140 cm and 155 cm.

From Fig. 13a–c, it can be observed that at 90% and 100% degrees of compaction, C40 sample (with about 60% fines and 40% sand fraction) shows more resistance to erosion. The larger sand particles help in better holding of fines that have some cohesion. When compacted to 80%, the moulding water content is very less, and consequently, the cohesion is less. At 90% compaction (dry side), the results are similar to the ones observed when the soil is compacted to maximum density at a moisture content corresponding to 50% of OMC. Due to particle dispersion at lower heads, a higher rate of erosion is observed. When the soil is compacted to 100% compaction density at OMC, an increase in head causes an increase in erosion rate.

Fig. 11 Variation of **a** erosion rate index (I_h), **b** coefficient of soil erosion, C_e , of M samples compacted at OMC (Note: W denotes wash off occurred beyond this head)

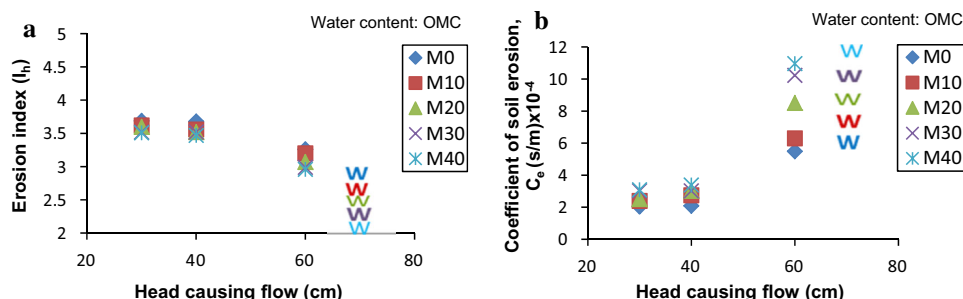


Fig. 12 Variation of **a** erosion rate index (I_h), **b** coefficient of soil erosion, C_e , of M samples compacted at 106% of OMC (Note: W denotes wash off occurred beyond this head)

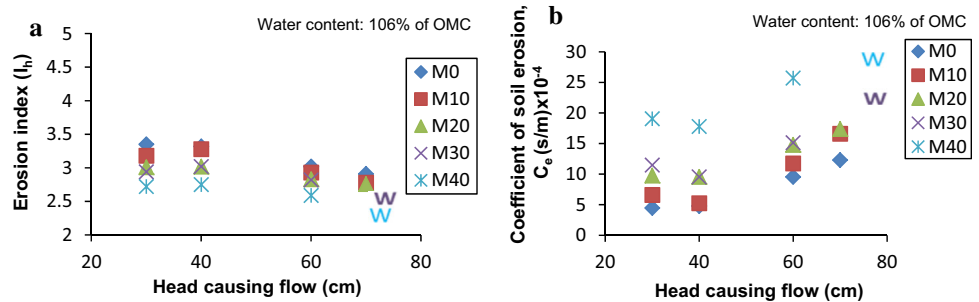
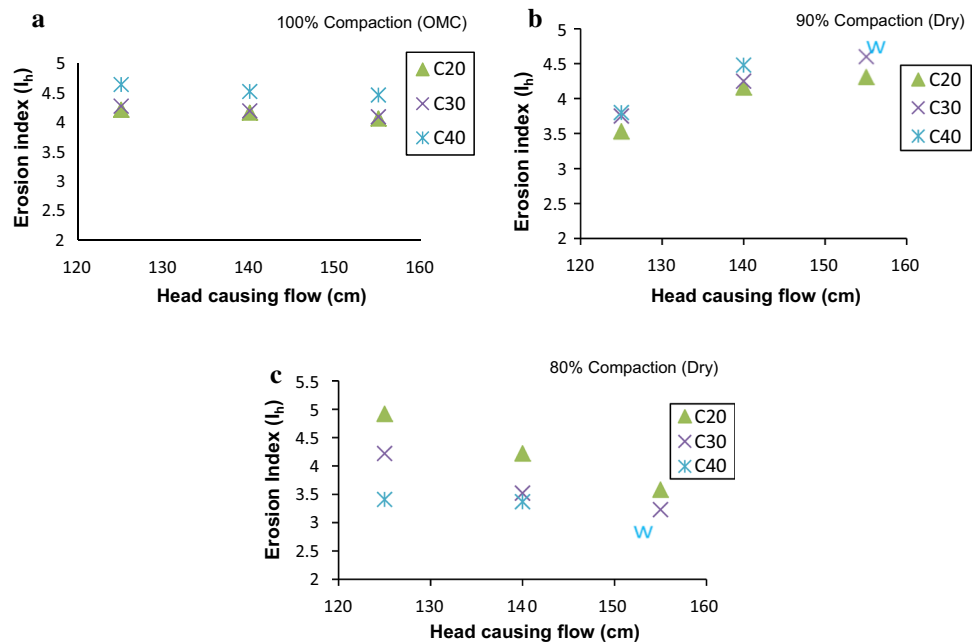


Fig. 13 Erosion rate of C samples compacted to **a** 100% relative density, **b** 90% relative density, **c** 80% relative density (Note: W denotes wash off occurred beyond this head)



It can be inferred that all the samples tested show better stability against erosion when better compacted, especially at smaller heads.

M Samples

The influence of compaction on M samples was studied with M20, M30 and M40 samples. Soil samples were compacted to 80%, 90% and 100% of their maximum dry densities. The water contents were taken on the dry side of the corresponding light compaction curves. Specimens were tested at heads of 30 cm, 40 cm and 60 cm.

At 80%, 90% and 100% degrees of compaction, M20 sample (with about 80% fines + 20% sand) is more erosion resistant (Fig. 14a–c). This is perhaps because of good gradation and higher cohesion between the soil particles.

Also the M40 samples (with about 60% fines + 40% sand) are least stable as the sand fraction is high, probably reduced cohesion, causing it to erode more. It can be observed that all the samples show maximum stability when compacted to its maximum dry density and have least

stability when compacted to 80% of its maximum dry density.

Figure 15a, b shows the settled soil particles in the overflowing container in case of wash off and erosion, respectively. Trials were attempted on samples compacted to 90% and 80% wet of optimum for both C and M samples. But due to the higher water content, the sample collapsed when the hole was drilled and placed horizontally for the experiment (Fig. 16).

Influence of Change in Initial Hole Diameter

To determine the influence of initial hole diameter in HET, C samples were compacted to their maximum dry densities at their corresponding optimum moisture contents. Holes of 8 mm diameter were drilled in the specimen, and the tests were conducted. The erosion rate index varies from 3.59 to 4.68 (Table 4) and can be classified under moderately rapid to moderately slow erosion, similar to as that of samples with 6 mm diameter. Table 4 also shows values of erosion

Fig. 14 Erosion rate of M samples compacted to **a** 100% relative density, **b** 90% relative density, **c** 80% relative density

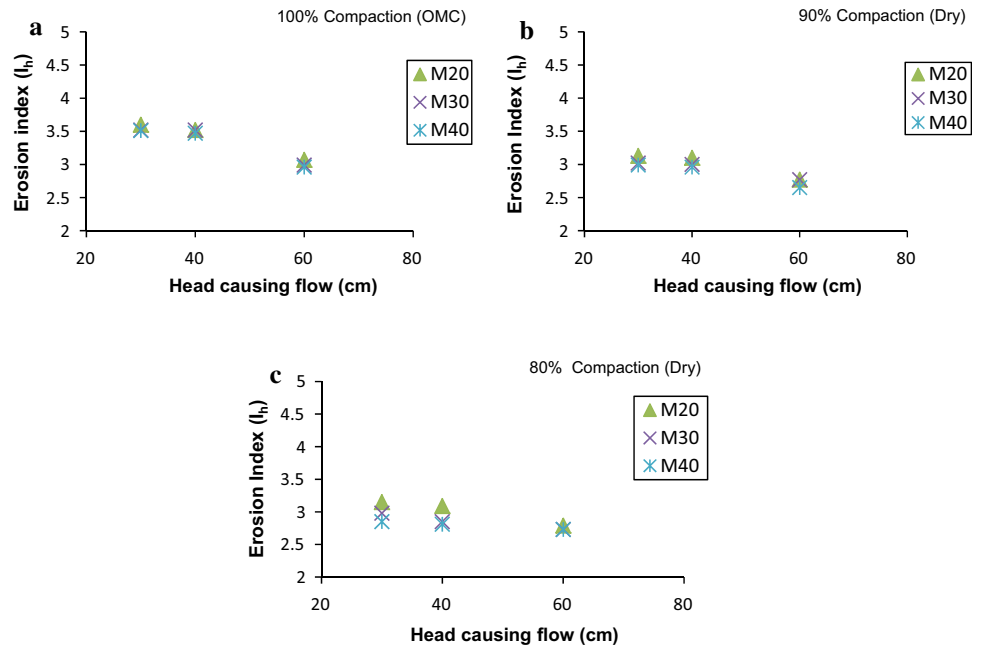


Fig. 15 Settled soil particles in the overflowing container in case of **a** wash off, **b** erosion

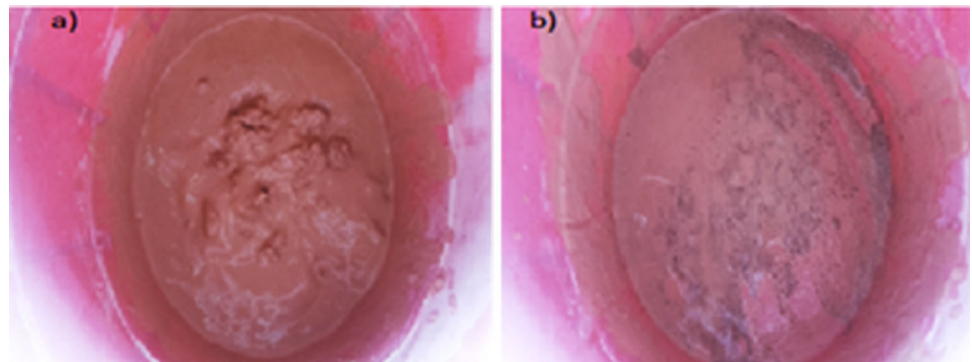


Fig. 16 Sample which collapsed when compacted to 90% wet of optimum

rate index (I_h) for 6-mm-diameter holes in brackets for comparison. This comparison is also shown in Fig. 17a–e.

It is observed that the initial hole diameter does not influence the erosion rate index significantly. Hence, the

initial diameter is not a very significant parameter affecting the test results and rate of erosion remains fairly constant for a given dry density, head causing the flow and water content, irrespective of hole diameter.

Critical Shear Stress

Critical shear stress is defined as the minimum stress to be applied on the soil surface to initiate progressive erosion. The average critical shear stresses obtained for different soil samples at various moulding water contents are shown in Fig. 18a, b. In general it is found that at optimum moisture content condition, the soil is most stable and shows a higher value of critical shear stress.

In the case of C samples, critical shear stress varies from 200 to 400 N/m². At 110% OMC (i.e. full saturation condition), since C0 sample was most stable it has the highest value of critical shear stress. At OMC and 50% OMC

Table 4 Erosion rate index of C samples at OMC and maximum dry density condition conducted with an initial hole diameter of 8 mm

Head(cm)	Erosion rate index (I_h) (values in brackets are for 6 mm hole diameter)				
	C0	C10	C20	C30	C40
110	3.78 (4.26)	4.16 (4.35)	4.52 (4.50)	4.67 (4.52)	4.68 (4.84)
125	3.72 (4.03)	3.91 (4.13)	4.26 (4.21)	4.26 (4.27)	4.61 (4.64)
140	3.64 (3.94)	3.83 (4.06)	4.02 (4.16)	4.03 (4.19)	4.56 (4.52)
155	3.59 (3.89)	3.64 (3.97)	3.85 (4.06)	3.91 (4.09)	4.32 (4.46)

Fig. 17 Comparison of Erosion rate index obtained for **a** C0 sample, **b** C10 sample, **c** C20 sample, **d** C30 sample, **e** C40 sample with initial hole diameter 6 mm and 8 mm

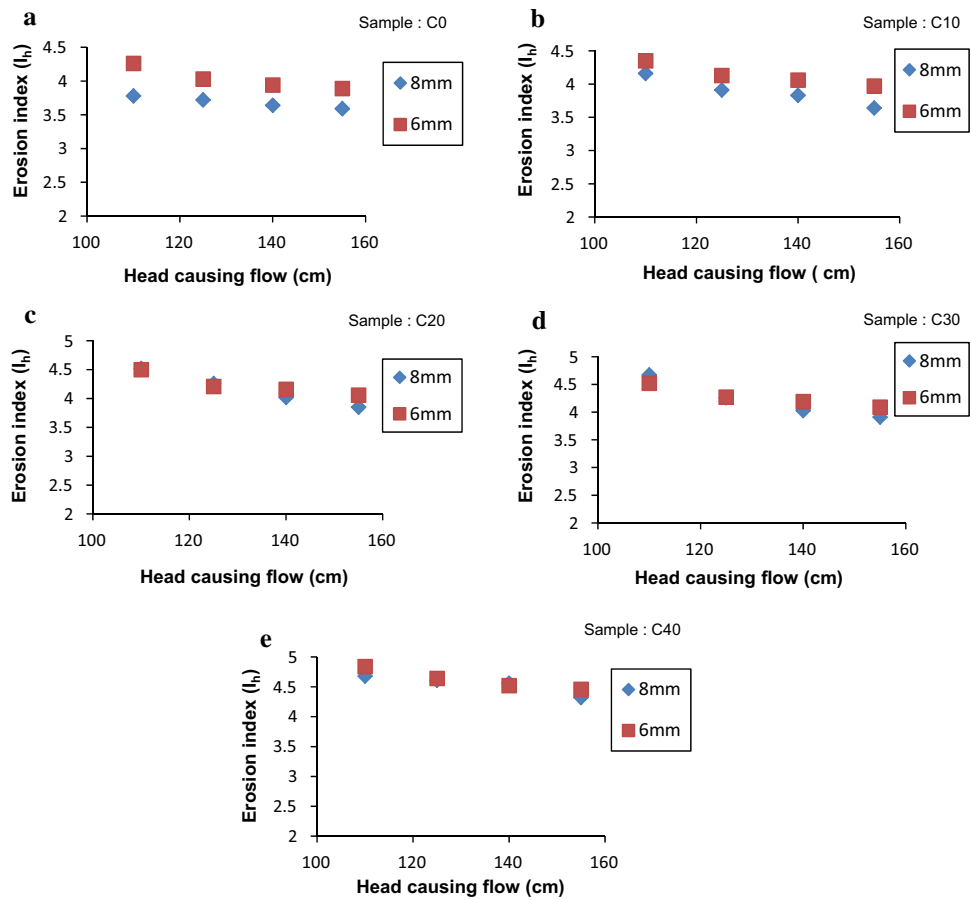


Fig. 18 Critical shear stress variation of samples at different moulding water contents for **a** C samples, **b** M samples

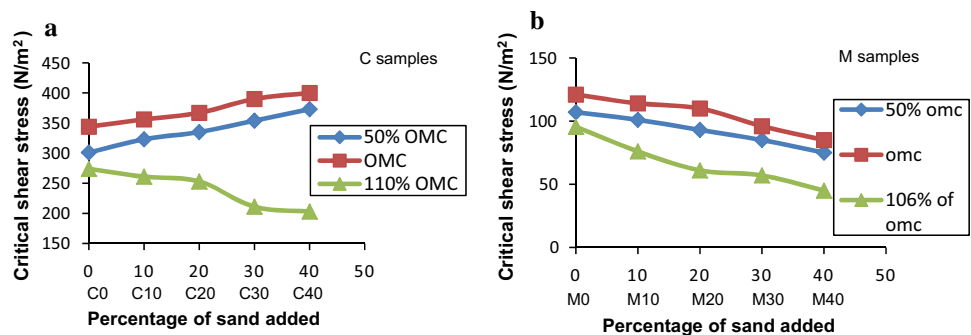


Table 5 Percentage of silt for all the blended samples with varying percentage of sand added

Percentage of sand added to C and M samples ^a	Percentage of silt fraction (2 μ to 75 μ size)			
	C samples		M samples	
0 ^b	C0	42.7	M0	79.9
10	C10	38.4	M10	74.5
20	C20	34.2	M20	64.1
30	C30	30.7	M30	55.1
40	C40	26.3	M40	51.0

^aC samples procured from source 1 and M samples procured from source 2

^bNatural procured sample

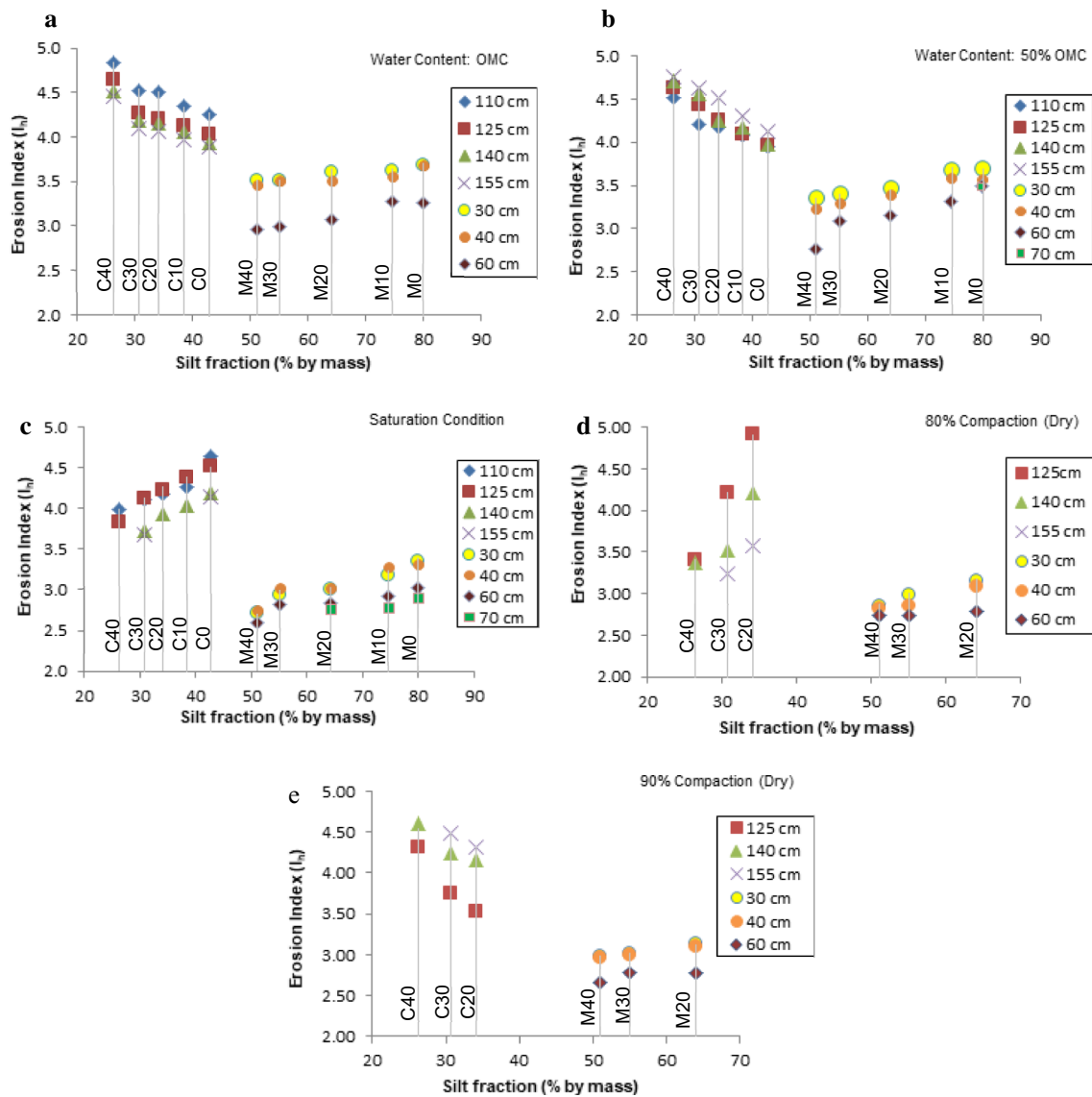


Fig. 19 Variation of erosion index of samples with silt content for **a** OMC condition, **b** 50% of OMC condition, **c** saturation condition, **d** 80% compaction, **e** 90% compaction

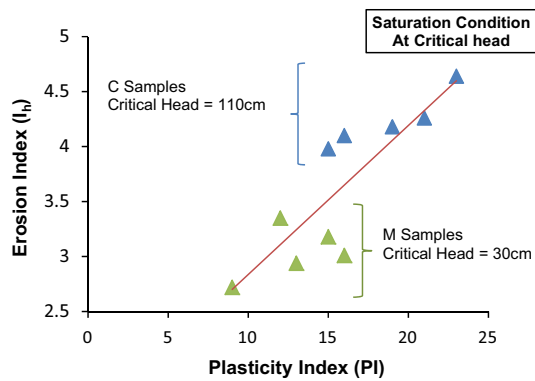


Fig. 20 Variation of erosion index (I_h) with plasticity index (PI) at critical head (samples prepared at saturation condition)

conditions, C40 sample being more stable shows a higher value of critical shear stress.

In the case of M samples, critical shear stress varies from 45 to 125 N/m². At all the initial moulding water content, M0 sample shows a higher value of critical shear stress.

It can be clearly observed that soils with higher silt content (M samples) show a lower critical stress than those of soils with higher clay content (C samples).

Variation of Erosion Index with Silt Fraction

A comparison of erosion rate indices is studied for the M samples (having comparatively higher silt content) and C samples to understand the influence of silt content on erosion index values.

From Table 5, it is clear that the M samples have higher percentage of silt fraction (2 μ to 75 μ size) when compared to the C samples. Figure 19a–e shows the variation of erosion index with silt content for different conditions of water content and compaction.

It is observed that the C samples have lower erosion rate when compared to the M samples which have higher silt content. Since the M samples have higher silt content (silt fraction), the structure of soil mass is less stable. However, in the C samples, as silt content is less, the structure of soil mass is more stable with the fine clay particles filling the voids of the coarser particles leading to higher interparticle shearing resistance and higher stability of the C samples.

Variation of erosion index (I_h) with plasticity index (PI) at saturation

The variation of erosion index with plasticity index for all the samples prepared at saturation condition and at critical head is analysed and is shown in Fig. 20. In the field, after heavy rain, caving in is observed in the slopes in lateritic formations, with exposed lateritic soils (lateritic lithomarge

or lithomargic laterites). The soil gets fully saturated and undergoes erosion. This was being simulated in the laboratory by preparing samples at fully saturated condition and then conducting the hole erosion tests. From Fig. 20, it can be observed that erosion index (I_h) increases with increase in plasticity index (PI). This indicates that higher the plasticity index higher will be the erosion resistance of the soil. Critical head indicates the minimum head (and thereby representing critical shear stress) at which the soil sample in laboratory will undergo progressive erosion in a hole erosion test.

Conclusions

Hole erosion tests are conducted on lithomargic clay samples containing higher clay fraction (C samples) and higher silt fraction (M samples). Soils containing higher clay fraction showed higher resistance to erosion with critical shear stress varying from 200 to 400 N/m², whereas in the case of soils with higher silt fraction lower erosion resistance was observed, with critical shear stress varying from 45 to 125 N/m². Critical shear stress was observed to be higher for all the samples prepared at OMC conditions indicating greater resistance to erosion. Soils with high plasticity index were less susceptible to erosion than soils with lower plasticity index. Lithomargic clays with higher clay fraction could be classified under moderately slow erosion, whereas soils with higher silt fraction indicated very rapid to moderately rapid erosion.

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