Correlation of CBR with Density and Moisture Content

by

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Introduction

Current practice in many countries is still to make use of the California Bearing Ratio (CBR) test for assessing subgrade properties for flexible pavements. A number of attempts have been made in the past to correlate CBR with some fundamental properties of soils such as plasticity data, grain size distribution, bearing capacity, modulus of subgrade reaction, modulus of resilience and shear strength. Black (1962) has developed predictive models for CBR from plasticity data. He also showed that CBR values can closely predict bearing capacity of soils. Agarwal and Ghaneker (1970) have reported a similar approach for the prediction of CBR from plasticity characteristics of soils. Nascimento and Simoes (1957) have related CBR with the modulus of strength which is the product of the modulus of subgrade reaction and the diameter of the loading plate. They concluded that the modulus of strength is 10 to 20 times the CBR for soft meterials and 10 to 30 times for hard materials. Huekelom and Forster (1960) have correlated the modulus of elasticity with CBR using wave propagation techniques. Huekelom and Klomp (1962) summarized the work carried out at Shell laboratories and Transport and Road Research Laboratory (TRRL) and showed that the general trend is represented by the relationship $E = 10 \times$ CBR (MPa) with a scatter of results such that they could differ from this by a factor of two. The Asphalt Institute has originated thickness design charts for flexible pavements based on CBR values. In order to facilitate the use of these design charts the Asphalt Institute (1981) suggests that the modulus may be approximated from the relationship $E = 10.342$ CBR (MPa) or $E = 1500$ CBR (psi). This correlation is considered valid for materials that are expected to have a modulus of 207 MPa (30,000 psi) or less. Because various correlations between CBR and different fundamental soil properties are now available and the engineers have gained wide experience, CBR test remains a popular method.

Extensive laboratory tests have been conducted at Roads Laboratory, Ministry of Public Works, Kuwait, during the past several years to determine CBR, maximum dry density and optimum moisture content of soil samples received for routine quality control of subgrade consruction. CBR is only an arbitrary number and the test is time consuming. Also, the CBR test is found to be sensitive to changes in the moulding moisture content and dry density. To obtain representative values with the minimum effort, a need to correlate CBR with moisture and density was felt.

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Using the results of routine tests for quality control of subgrade construction, general relationships between CBR, maximum dry density and optimum moisture content for different soil types classified according to AASHTO became apparent and attempts were made to establish possible correlations by statistical methods. It is the principal purpose of this paper to point out such correlations. From such correlations one can readily obtain an approximate value of CBR for a given type of soil whose maximum dry density and optimum moisture content values are known. Since the actual determination of CBR will not be absolutely required owing to the availability of such empirical relationships, much time can be saved for the preliminary evaluation of the performance of soils primarily for use as subgrades beneath pavement surfaces.

Standard CBR and Compaction Tests

Compaction tests conducted were in accordance with AASHTO Designation T 134-76, Method A, which involves laboratory densification of soil in five equal layers in a 943.9 cm^3 mould. Each layer is subjected to 25 blows of a 4.54 kg. hammer falling 45.7 cm. Determining the CBR value in each case was carried out at optimum moisture content after soaking the sample in water for four days in accordance with AASHTO Designation T 193-72.

Development of Statistical Correlations

Study of the past records used in this work revealed that four types of soils are generally encountered in Kuwait viz. *A-1-b*, *A-3*, *A-2-4* and *A-4* according to AASHTO classification system with *A-2-4* being the most common type of soil. In order to establish a functional relationship between CBR as a single dependent variable and maximum dry density and optimum moisture content as two independent variables, the following regression model was found to be appropriate and was tested for each soil classification :

$$CBR = a + b\,(OMC) + c\,(MDD)$$

where a, b and c are regression constants;

OMC is the optimum moisture content (%);

MDD is the maximum dry density (gm/cm^3).

The method of least squares was used to estimate the regression parameters a, b and c. The relationship obtained for A-2-4 soils is described by the following equation :

$$CBR = -147.74 + 1.49\,(OMC) + 78.10\,(MDD)$$

The coefficient of correlation (R) corresponding to this equation has worked out to be 0.84 which means that 70 per cent (viz. $R^2 \times 100$) of the variance in the data is taken care of by this equation. The standard error of estimate (S_e) calculated is 2.10. At 95 per cent confidence level, the laboratory CBR value would fall within $\pm$ two standard errors of estimate as obtained for the regression equation. Table I gives a summary of all the correlations developed.

TABLE I

Prediction Equations for CBR

AASHTO Classification	Model	S_e	R	$R^2 \times 100$	No. of Samples
A—1—b	CBR = −219.46+3.07 (OMC)+106.69 (MDD)	±1.73	0.88	78	56
A—3	CBR = −188.78+2.15 (OMC)+ 97.88 (MDD)	±1.42	0.93	86	138
A—2—4	CBR = −147.74+1.49 (OMC)+ 78.10 (MDD)	±2.10	0.84	70	344
A—4	CBR = 187.81—3.12 (OMC)— 69.71 (MDD)	±1.78	0.88	78	28

R = Correlation coefficient; R^2 = Coefficient of determination: S_e = Standard error of estimate.

Based on the correlation coefficients as shown in Table I, it may be assumed that each of the correlations established would give a reasonable approximation of the CBR value from laboratory moisture-density tests. However, while determining the acceptability of the correlations, the standard error of estimate should also be considered. The decision as to whether the standard error is acceptable is left to the statistical and engineering judgement of the user.

With a view to confirming the validity of CBR values predicted by using the correlations as shown in Table I, additional actual tests were performed. Good agreement was observed between the CBR predicted from the established correlations and that measured by these additional check experiments. The correlations presented in this paper are currently being used by the Roads Laboratory, Kuwait and have proved to be a simple and a quicker method for the approximate estimation of the CBR value for a soil with known maximum dry density and optimum moisture content.

Discussion

The CBR of a soil largely depends upon the type of soil, amount and the method of compaction, dry density and the moulding moisture content. The correlations are valid only for the given compaction and test conditions of this study. The maximum dry density and optimum moisture content values to be used must have been derived from standard tests mentioned earlier. In many cases, CBR values at combination of dry density and moulding moisture content otherthan optimum are required. In such cases, the use of regression equations is restrictive as they are applicable only for CBR values at maximum dry density and optimum moisture content.

It is to be emphasized that the correlations presented here are based upon a particular range of moisture content and CBR values pertaining to Kuwaiti soils. Table II gives a summary of the ranges of optimum moisture content and CBR values for different soil types encountered in Kuwait. It would not be appropriate to use the correlations for those optimum moisture content values outside these ranges. As seen from Table II, the actual minimum CBR values for Kuwaiti soils are relatively

TABLE II

Ranges of CBR and OMC Values

Soil Type (AASHTO Classification)	CBR Range (%)	OMC Range %
A—1—b	10 to 40	5 to 11
A—2—4	9 to 46	6 to 12
A—3	12 to 51	6 to 14
A—4	8 to 25	7 to 14

high. Many problem soils generally have CBR values considerably less than 8 per cent. Thus, it is a limitation on the correlations that the soils having CBR values lower than 8 per cent were not encountered during the routine laboratory tests.

The engineer attempting to use the correlations presented in this paper must be cautious because the soils from different regions having the same soil classification are often found to exhibit many large deviations in their fundamental behaviour. Appreciable variations are observed in the quality of subgrade soils in the Arabian Gulf area when compared with soils from other regions having the same AASHTO classification. Kuwaiti soils are generally calcareous in nature and contain gypsum, salts of calcium, magnesium and sodium sulphates in varying proportions (Bissada and Qabazard, 1974). The presence of these materials provides adequate strength which, however, drops considerably under soaked conditions. Figure 1 shows how the CBR of a typical Kuwaiti calcareous sand, locally

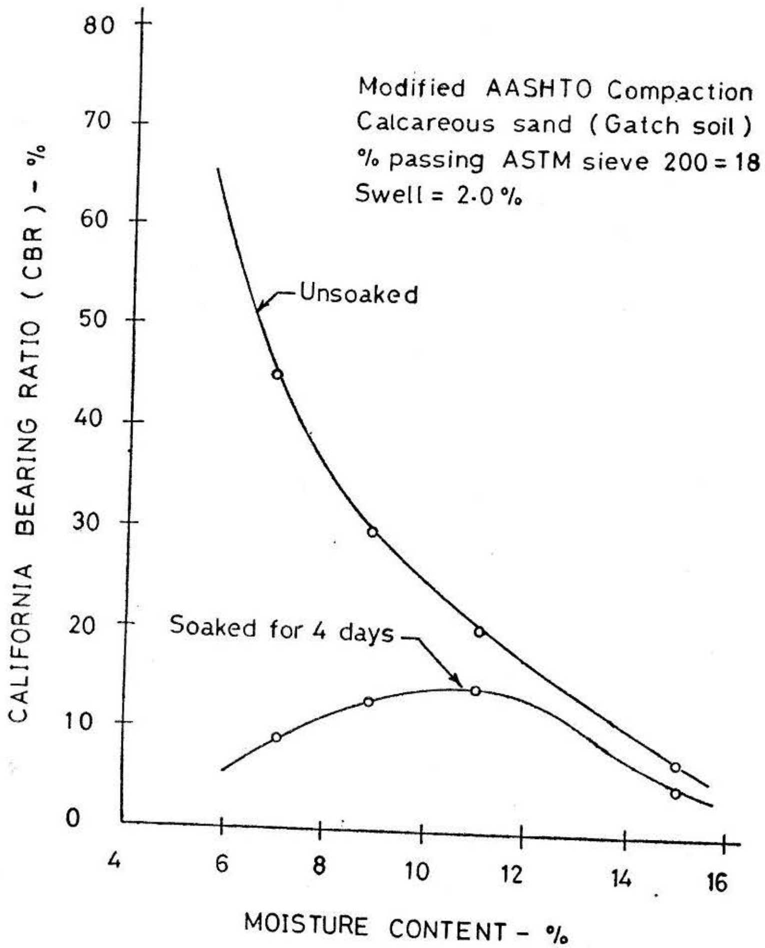

FIGURE 1 Relationship between CBR & moisture content

named "Gatch", is dropped under soaked conditions for different moulding moisture contents. This supports why a CBR range of 9 to 46 measured for Kuwaiti *A—2—4* soils contradicts the CBR values greater than 50 as reported in the literature based on an approximate correlation of AASHTO classification with CBR and bearing capacity as originally proposed by Fruhauf (1946). Figure 2 shows a comparison of CBR ranges for Kuwaiti soils with those suggested in the literature including the thickness design curves of Asphalt Institute (1970). Thus, in certain cases it may not be appropriate to follow this correlation without any regard to the inherent physicchemical characteristics of a particular soil.

In view of the above, it is possible that correlations different from those presented in this paper may be obtained for other areas. Therefore, the development of similar correlations on regional basis is highly recommended.

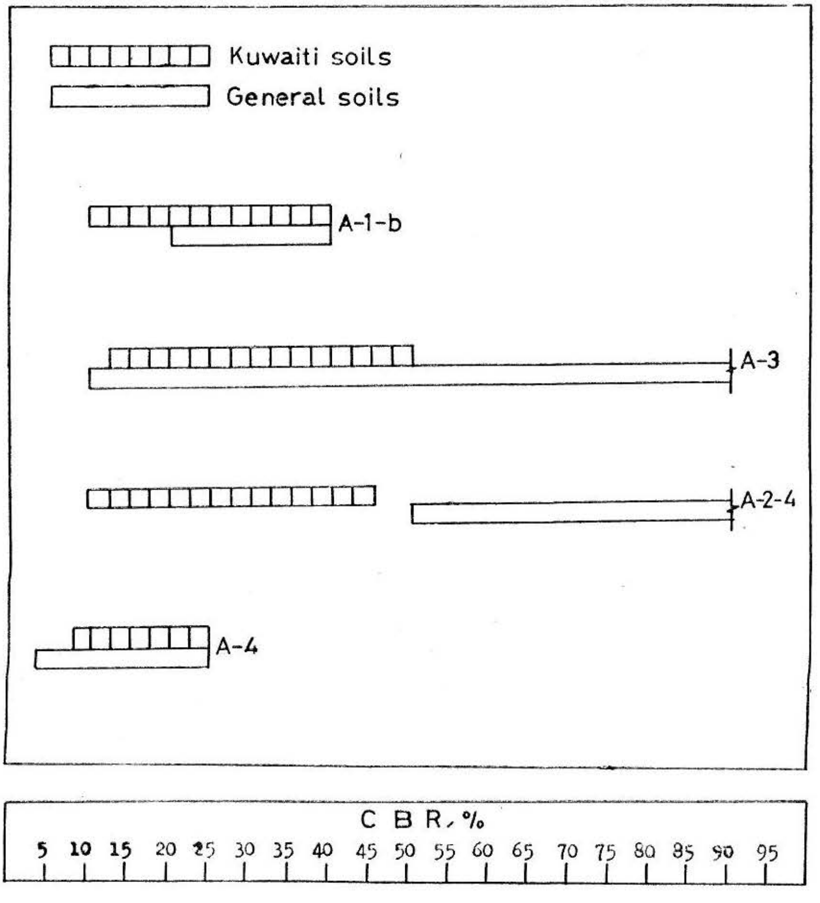

FIGURE 2 Comparison of CBR values of Kuwaiti Soils

Conclusions

Correlations of CBR with maximum dry density and optimum moisture content for different soil classifications have been established for Kuwaiti soils. Although the scope of this study is limited, it supports the view that it is possible to predict a rough approximation of the CBR value from a routine moisture-density test.

Although the correlations developed have been found to be reliable and useful for Kuwait, limitations as discussed previously should be considered when using them.

Acknowledgement

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Recent Trends in Design and Construction of Slurry Trench Cut-off Walls

by

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Introduction

In projects involving seepage cut-offs, dewatering and pollution control etc. slurry trench cut-off walls have become almost an integral part of the construction. Usually cut-off walls are cheaper, more efficient and simple in construction than other systems used for the same purposes.

The history of slurry cut-off wall construction in geotechnical engineering is not very old. The first reported use of slurry cut-off wall is in early 1940's in the United States and since then thousands of slurry cut-off walls have been constructed for various applications of temporary and permanent nature. Many buildings have been made by using this technique which otherwise would not have been possible because of prohibitive construction costs and technical difficulties. This technique has now gained importance in almost all parts of the world and rapidly it is replacing the traditional techniques of grouted cut-off, sheet piles, diaphragm walls etc.

Before development of slurry cut-off wall technique, diaphragm walls were used to serve the same purpose. In diaphragm wall construction a narrow trench is excavated using bentonite slurry to provide lateral support of the trench. After completion of the excavation of the segment of the trench either cast in situ concrete (tremmie process) or precast panels are installed by replacing the slurry. These walls serve either as a cut-off walls or load bearing walls. The slurry cut-off walls are different from diaphragm wall construction as in this case reinforced concrete is replaced with either soil-Bentonite (*S—B*) slurry or cement-Bentonite (*C—B*) slurry. Further experience and research have indicated various new compositions of ingredients which optimize the construction and give best results. Nevertheless the data for different field conditions concerning the engineering properties of cut-off materials and its performance in long run is scarce. The greatest contribution to this technique came from the American constructors who thought of technique's versatility and found its merits. They used *S—B* slurry for the purpose. Thereafter European constructors followed suit and they adapted the technique in somewhat different manner. They used *C—B* slurry as the final ingredients of the wall.

This paper addresses the critical design issues, reviews the current construction practice of *S—B* and *C—B* slurry walls.

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Applications

Various common applications of slurry cut-off walls are shown in Figure 1. Because of economic reasons and the simplicity in construction, the slurry walls are finding ever increasing applications. Primarily slurry walls are used to create an impervious isolating media. Usually the wall is extended to the lower impervious strata and keyed into it. The lower impervious strata may be rock, clay etc. in which the wall is keyed atleast 60 cm. to provide effective isolation. If it is not feasible to extend the wall into the impervious strata, wall is constructed sufficiently deep to minimize the percolation of fluid.

Dewatering

Some of the conventional dewatering means are open sumps, well points, deep wells, electro-osmosis, grouting, compressed air, ground freezing etc. Sometimes these methods are difficult to use and uneconomical. In numerous projects, slurry cut-off walls have been used more effectively for the purpose. It is specially recommended for projects adjacent to rivers, streams, ponds etc. which are continuous source of ground water supply. In such situations, conventional methods are ineffective and dangerous.

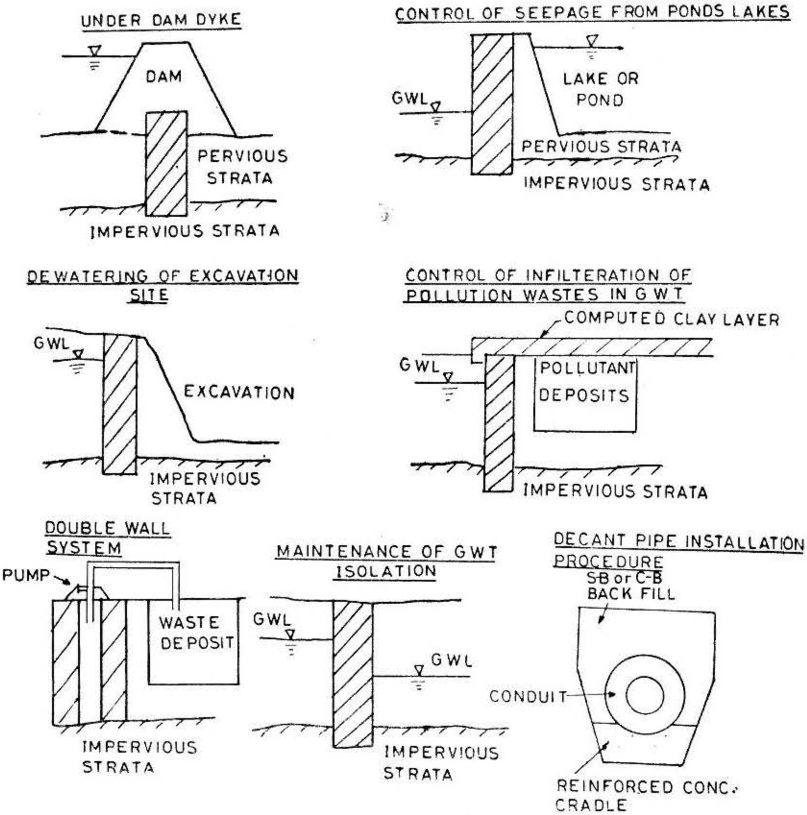

FIGURE 1 Various Applications of Slurry cut-off Walls

The slurry cut-off walls offer various advantages over conventional pumping system. For example it eliminates the :

1. Pumping of water;
2. Equipment maintenance and man power cost ;
3. Flooding of water;
3. Risks due to system breakdowns, strikes, power failures etc.
5. Damages due to lowering of water table such as settlement of adjacent structures, crop damage etc.

A site sealed by slurry cut-off walls provides dry construction area.

Seepage Barriers

Slurry wall constructions have been effectively used as seepage barriers under a dam, to repair a leak, to extend core of the dam downward into the underlying strata and to prevent seepage in the basement of buildings located near water source.

Waste Isolation

Slurry trench cut-off walls can very effectively be used for waste isolation purposes. The increasing consciousness against industrial pollution have made this technique very attractive as it offers economical and simple construction for disposal of industrial wastes.

In the waste isolation system, the construction procedure consists of three stages. First, below the dump area impervious strata is required which can be made by concreting the base or by compacted clay layer. In stage 2, slurry cut off walls are constructed. And finally, the dump is covered by compacted clay layer. Thus, the dump is totally isolated from surrounding environment. Experience has shown that the such constructions are durable and very effective in isolating the wastes. The future expansion of dump site can be made with marginal cost.

In case of ground water pollution control, permeability is the most important parameter. Very low permeability is required in hazardous waste isolation case. Permeability of the wall depends upon the composition of materials in the wall and with properly selected materials, one can get the permeability of the order to 10^{-9} cm/sec. If even a slight leakage from the waste is likely to pollute the ground water, a system involving double lining of the wall can be opted successfully. Leachate which passes through first lining of wall is pumped back to the main waste before passing through the second lining. This system is specially recommended for the disposal of hazardous chemical wastes, sewage dumps, acid mine wastes etc. where 100 per cent isolation is required.

In case of chemical isolation, precaution should be taken in selecting the wall materials. Commonly used wall construction materials are more susceptible to very high basic waste than acid waste and generally recommended pH range is 2-10. In case of highly acidic or basic wastes the wall material should be tested for chemical actions of waste and, if found suitable, it may be used. Otherwise it may lead to higher permeability of wall due to chemical action of waste. At some construction sites, pretreated wall materials have been successfully used.

Other uses

Slurry walls can also be used for chemical waste collection, storage and pumping for maintaining difference in water tables on two sides as shown in Figure 1.

Working Principle

Basically bentonite is sodium montmorillonite which has liquid limit (w_L) of approximately 190 per cent and plastic limit (w_P) in the range of 31-47 per cent though these values may vary for different brands of bentonite. When bentonite is mixed with water, it swells and forms a viscous fluid called bentonite water slurry ($B—W$ slurry). It is formed due to breaking down of bentonite to flakes, about $10A°$ thick (Mesri et. al. 1970). In this stage, it does not offer shear resistance and so it can be deformed easily. When mixed with scil to make $S—B$ slurry, it becomes more viscous but retains many properties of $B—W$ slurry. While if cement is added to form $C—B$ slurry, it settles and sets after some time and forms a permanent cut-off wall.

A trench filled with slurry is a very low permeability structure which does not allow fluid flowing from one side of the trench to other side of the trench. Three main advantages are :

1. Fluid cannot replace water attached to bentonite due to chemical bonding and therefore transmission of fluid through bentonite slurry is prevented.

2. Bentonite slurry acts as a continuous wall without voids so water cannot infilterate it.

3. Bentonite slurry penetrates the voids of trench walls and chokes the water bearing conduits.

In case of S-B slurry trench wall, water pressure is taken by the wall. Even high pressures does not cause failure of the wall as it deforms easily rather than breaking and would not facilitate water migration. In case of C-B slurry walls, first voids are choked by slurry like grouting and then the solid wall with very low permeability which does not allow fluid to pass through it (Figure 2). It can also take some vertical or lateral loads.

The basic properties of the both types of walls are very low permeability, deformability, and permanence. The permeabiliiy of a completed *S-B* slurry cut-off trench is a function of both the fllter cake that forms on the trench wall due to B-W slurry and permeability of the backfill in the trench. In case of *C-B* slurry cut-off trench, permeability depends on the backfill only. Accordiug to D'Appolonia (1980), permeability of a *S-B* cut-off is given by

$$K = \frac{t_b}{\frac{t_b}{K_b} + \frac{2t_c}{K_c}}$$

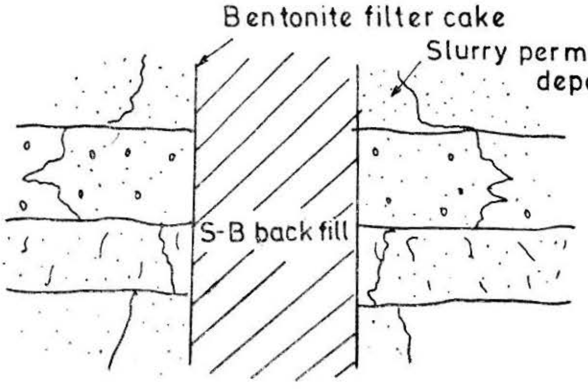

FIGURE 2 Cross Section of S-B Slurry Trench Cut-off

where t = thickness; K = permeability; subscripts c and b refer to filter cake and S-B backfill respectively; and symbols without subscript refers to the overall cut-off wall. $\frac{K_c}{t_c}$ values were reported to vary between the narrow limits of 5×10^{-9} cm/sec. to 25×10^{-9} cm/sec. for a wide variety of practical applications.

Though the filter cake has very low permeability but generally it is not accounted for in the design for the principal reasons that it has a very low thickness and possibility of scrapping-up when backfilling and rupturing off due to high gradient of water can not be ruled out. It has been found that in *S-B* slurry, permeability varies depending upon the mix compositions in order of 10^{-9} cm/sec. and in *C-B* slurry, containing equal volume of cement and bentonite the permeability is in order of 9×10^{-7} cm/sec. (Makhol et. al. 1981).

Normally one end of the wall is on the ground surface while other end is preferably keyed into some impervious strata (Figure 3). In some applications such as in dams, both ends of wall are beneath the ground surface. In such applications settlement due to consolidation and deformation should also be taken into account as it may reach even upto 10 per cent of the total depth of the wall and may cause leakage on the top end of the wall.

Life of bentonite slurry trench cut off walls depends upon the environment. In normal environment slurry trench cut-off wall would be long lasting. In hostile environment permeability of the wall would be reduced with time and thus effective life of the wall is reduced. In toxic wastes, trench wall material can be dissolved For example amorphous silica, an ingredient of *S-B* slurry is dissolved in highly basic solutions. Phenomenon of substitution of pore fluid can also take place. Thus great care is required in selection of ingredients of wall and its composition specially when it is used for confinement of waste disposal.

Construction Methods

There are many steps in slurry trench cut-off wall construction. First,

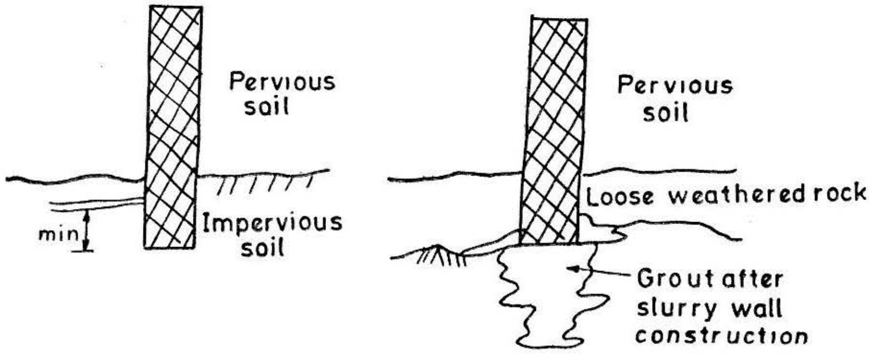

FIGURE 3 Slurry Trench Bottom Keys

a trench is made and simultaneously bentonite-water slurry is poured in the trench to keep the side walls from caving in. Different earth moving machineries which have varying capacities, specifications, and performances can be used to excavate the trench. The machine for the trench excavation is chosen according to the needs for the optimum and efficient use. The specifications and performance remarks for the various commonly used machines are given in the Table I.

TABLE I

Specifications of Earth Excavating Machines

Excavator	Max. Depth m (ft)	Min. Width m (ft)	Remarks
Back hoe	12 (40)	0.75 (2.5)	Very economical, fast excavation.
Dragline	30 (100)	1.50 (5)	Economical at higher depths.
Clamshell bucket	75 (250)	0.45 (1.5)	Higher cost slow production.
Vibrating pile hammer	18 (60)	0.05 (.2)	High quality control required not very reliable.

Trench is made as thin as possible because with increasing width the cost of construction becomes very high and no significant reduction in permeability is obtained. The cost of construction also depends on the speed of excavation. Excavated material is placed near the trench as most of it is reused again as a backfill in *S-B* slurry wall.

Bentonite slurry

The slurry placed in the trench performs 4 main functions. These are :

1. To hold the trench open upto the required depth.

2. To be workable so as to allow movement of excavating equipment and displacement by backfill.

3. To be impermeable.

4. To be deformable so not to fail when lateral pressure is applied.

B-W slurry has been successfully used to keep the trench open upto the 105 m depth and 1000 m long. A typical *S-B* slurry wall is shown in Figure 2.

Bentonite slurry is made by hydration of bentonite. Hydration process begins the instant when water is added to bentonite. Generally two types of mixing are done to get B-W slurry. These are :

1. Flash mixing : In this process dry bentonite is exposed to highly turbulent water jet that discharges into a low speed circulation tank where bentonite is hydrated. This type of mixing is efficient when bentonite slurry is required on a large scale.
2. Vortex mixing : In this process high shear vortex is used to prepare the slurry. Slurry remains in the mixer until hydration and thereafter it is placed in the trench directly. This process is good for small scale *B-W* slurry use.

The duration of hydration is a function of mixing system used, bentonite type, chemical properties of water, duration of mixing etc. Effect of water temperature on slurry properties is not significant. High concentration of electrolytes in water is not preferred.

The percentage of bentonite in the slurry depends upon the bentonite type. Usually it is 5 per cent of bentonite by weight and from 25 kg. to 50 kg. per cubic meter by volume. Density of the obtained slurry varies in range 1.03-1.40gm/cc. Minimum density of slurry has typically been set slightly over that of ground water. To check the properties of bentonite slurry two tests are commonly used. These are :

1. Viscosity Test :

Viscosity is the most important parameter of bentonite slurry construction because lower viscosity may lead to failure of trench and higher viscosity would pose problem of workability. Viscosity is measured by Marsh tunnel method. Marsh tunnel viscosities should be in range of 40-50 Marsh sec. This range of viscosities has been found to give consistently reasonable results in ensuring the satisfactory excavation, stability and construction of *S-B* and *C-B* walls.

2. Filterate Test :

In this test, constant pressure is applied on slurry sample, pressing against the filter paper. Volume of water escaping is measured which is inversely related to degree of hydration and bentonite quantity. It gives an idea of volume of water which may be lost to the side walls of the trench. Filterate loss is indeed a measurement of stability of the slurry wall.

Filter loss and corresponding cake thickness is indicative of how much slurry loss will occur during excavation of the trench and how fast the cake will form or reform on the side of trench when damaged, e.g. by the excavating tool. To ensure a slurry of adequate quality the normal range of filter loss for bentonite slurries for *S-B* wall construction is from 15-30 cm^3 and for *C-B* slurry from 100-180 cm^3. Actually in *C-B* slurry, it is preferred to measure the filter loss of fully hydrated bentonite slurry before the addition of cement. The filterate loss should be maintained below 30 $cm.^3$

As mentioned earlier, two types of backfill are in use viz. *S-B* and *C-B* slurry. In *S-B* slurry, it is poured in the trench to displace *B-W* slurry. While in *C-B* slurry construction, it is mixed with *B-W* slurry to form a cut-off-wall thus dispensing with need of displacing operation of *B-W* slurry.

Soil-Bentonite slurry :

S-B slurry is preferred because the excavated material is reused as backfill thereby minimizing the material handling. The slurry in the trench gets mixed with trench material and it may not be suitable for further trench excavation. Part of this displaced *B-W* slurry is mixed with soil to prepare backfill and rest is mixed with fresh slurry to be used again. *S-B* slurry is prepared by sluicing the soil with *B-W* slurry and their it is tracked and blended until the homogeneous mix of proper consistancy is achieved.

The composition of the soil depends upon the final properties desired of backfill. A minimum 1 per cent bentonite and at least 20 per cent fines are required to get effective cut-off. To get even lower permeabilities clay content upto 60 per cent can be used. The backfill should also be able to perform functions of *B-W* slurry.

The prepared *S-B* slurry is then pushed at the point where backfill rises to ground surface, thus avoiding segregation. The backflll slides down the face of the previously placed backfill in form of a mudwave. Stiff backfill should not be used as it will cause folding and trapping of *B-W* slurry below the backfill. Unit weight of *S-B* slurry should be more than the bentonite slurry to dispose it easily. A minimum recommended unit weight is approximately 240 kg/m^3.

Cement-Bentonite Slurry :

In *C-B* slurry construction a wall is formed from cement-bentonite slurry which also stabilizes the trench during construction. Preparation of *C-B* slurry is done by two methods. In one method cement is added after several minutes of *S-B* slurry hydration. In another method cement is added to hydrated bentonite after flash mixing. Usually cement is mixed at the rate of 150 kg per m^3 of *C-B* slurry. Cement and bentonite slurry should not be mixed by compressed air because it would lead to formation of cavities due to airbubbles and it would reduce permeability of the wall.

In the batch mixing viscosity rises significantly due to the chemical activity of cement during hydration of bentonite. Viscosity may range upto 40 to 55 Marsh seconds. The higher viscosities are tolerable in *C-B* slurry as no backfilling is required. Initial filterate losses are around 5 per cent which upon addition of cement increase significantly with time until setting takes place. The final filterate loss of free water is around 50-60 per cent. (Ryan 1976).

Comparative evaluation of C-B and S-B backfill :

S-B slurry method is economical and avoids the problem of disposition of excavated material. On the other hand, *C-B* slurry method offers several advantages over *S-B* slurry method such as :

1. It is independent of in-situ soil quality as no backfill is required.
2. It is more suitable in areas prone to failure because it is easily repairable. If failure occurs, the failed portion after reinforcing can be tied to adjacent completed work.
3. Because of high strength *C-B* wall can be used as a structural member.
4. It offers better flexibility in construction schedule as trench can be excavated in sections and then keyed together to form a monolithic structure.
5. It offers homogeneous filling of slurry due to continuous stirring of the slurry from the excavating equipment.
6. Specially suited in congested areas as this method does not require additional adjacent place for mixing of backfill.

Final properties

In slurry trench cut-off walls what matters in the end is the final properties of the wall. It is immaterial what methods and processes were applied in the slurry wall construction. The final properties, that matters most, are :

1. Capability to hold trench walls
2. Impermeability
3. Permanence

The slurry wall should always stand so that trench does not collapse. It should also remain impermeable with time so not to allow transfer of fluids and it should also live upto its designed life. Besides these the properties of secondary importance are strength, compressibility, and flexibility which indirectly influence the functioning of the slurry walls. (Coron 1973).

On the basis of a full scale tests Ryan (1977) reported the permeability of *C-B* wall to be 3×10^{-6} cm/sec. and of the *S-B* wall to be 6×10^{-7} cm/sec. Even in sandy backfill which had natural permeability in the range of 10^{-4} to 10^{-5} cm/sec. permeabilities fell to the range of 2×10^{-7} to 6×10^{-7} cm/sec. upon mixing with bentonite slurry.

Final properties of *S-B* walls depend upon quantity and type of bentonite and presence of plastic fines in the backfill. Gradation and composition of the materials in the wall is also important as some backfilling materials may cause inhomogeneous distribution of material in the wall leading to increase in overall permeability. But the quantity of bentonite added should be within appropriate limits as no adding high amount of bentonite (>10 per cent) may cause cracking of the wall whereby increasing the permeability.

The strength of the slurry becomes an important consideration where loads on the wall are likely to be exerted due to adjoining construction equipment. The strength of the *S-B* slurry wall is generally very less and attain a maximum unconfined strength in the range of $0.7-1$ kg/cm^2 (10-15 psi). However in some cases it was found that the some walls never set up and maintained a consistancy like butter (Sherard 1960). On the other hand, *C-B* walls do set after some time and gain strength depending upon cement/water ratio and quantity of cement. Normally $2\frac{1}{2}-3\frac{1}{2}$ bags of cement per cubic meter are used and unconfined strength lies between 0.7 to 1.4 kg/cm^2 (10-20 psi) (Ryan 1977). The strength increases substantially under confining pressure and drained shear conditions. It is recommended that the *S-B* walls should not be constructed near the footing and if wall is likely to experience some pressure, *C-B* walls should be preferred.

Walls can be designed for required flexibility by varying bentonite and cement quantities. *S-B* backfill material containing between 10 and 40 per cent fines generally has a compression ratio of 0.02 to 0.07 with higher values associated with higher fines content. Low permeability and low compressibility are contradictory requirements because plastic fines required for lower permeability will give higher compressibility. Suitably selected materials can take deformation even upto 10 per cent without cracking.

There have been no reported failure or deterioration of any slurry trench cut-off wall. Generally slurry cut-off walls are not susceptible to erosion under normal environment. However, under hostile environment such as highly acidic or basic ground water and chemical wastes, cement may be attacked by sulphates and chemicals in ground water. (D'Appolonia, 1979).

Design Considerations

The primary design parameters, in their order of importance, are permeability, strength and compressibility. Besides other parameters such as deformability, and site environment are also to be considered. Following factors are considered in design of slurry walls; (*i*) continuity and integrity of wall (*ii*) thickness of the wall (*iii*) cut-off backfill properties (*iv*) backfill placement (*v*) stability (*vi*) strength.

Continuity and integrity of wall: Slurry wall design should be such that excavation is continuous and no seepage is permitted from joints. This can be achieved by controlling critical excavation tolerances, slurry properties and ground water conditions.

Thickness of the wall: It is based on the permeability required of the wall and practical field constraints. In case of *S-B* wall, thickness usually vary in the range of 1.5 to 2.3 m and in case of C-*B* wall, it is in the range of 0.6 to 0.9 m due to economic constraints.

Cut-off backfill properties: In case of *S-B* backfill bentonite should be 2-4 percent by weight, plastic fines passing through sieve # 200; 10-20 percent to get permeabilities around 10^{-7} cm/sec. Slump of 100-150 mm is specified and slope of backfilling 5:1 to 10:1 for the effective results. In case of *C-B* slurry, *C/W* ratio, *B/W* ratio and procedure for eventual pannel connections between the fresh cement bentonite slurry and *C-B* slurry should be specified.

Backfill placement : Backfill should be placed in wave form so that no trapping of *B-W* slurry takes place. Slope of 5:1 to 10:1 is specified to attain this (Millet et. al. 1981).

Stability of the trench: It is a function of water content, physical properties, shear strength, hydrostatic pressure, thickness of mud cake on the vertical wall, and horizontal arching effects due to slurry. Due to economic reasons loss in slurry should be minimized which depends on soil type, hydrostatic pressure, construction method, difference in height between ground water table and slurry level.

Strength: Under most conditions, it is required that slurry wall approximately attain the strength of surrounding ground. Stress change due to loading is avoided as it causes movement of the wall. In case of *S-B* backfill, it is assumed to have no strength but to be highly plastic. Normal *S-B* backfill at time of placing can stand a slope of 10:1 and after some times it improves to 2:1 (Horizontal: vertical).

Generally, *S-B* wall is assumed to be very plastic and thus highly compressible. A normal mix of *C-B* backfill can withstand compressive strains of several percent without cracking. Even if cracking occurs in wall due to large displacement, it will heal up the crack itself with passage of time. The strain at failure of a *C-B* slurry wall is partially dependent on cement-water ratio and on percentage of suspended solids present in backfill. This problem is more serious in sandy soils as presence of non-plastic and coarse materials decreases compressibility and increases permeability. This becomes a critical design issue if such materials are more than 10 percent and also at greater depths where percentage of such suspended solids increases. Figure 4 gives the data for selection of various parameters to obtain desired permeability.

Quality control is an important aspect of slurry wall construction. Periodic tests such as viscosity of slurry, density of slurry, slump of the backfill material, filterate loss etc. should be done during construction to check the quality of work done and introduce necessary improvements if required. Verticality of trench should be maintained and if required trench cleaning should be done prior to placement of slurry.

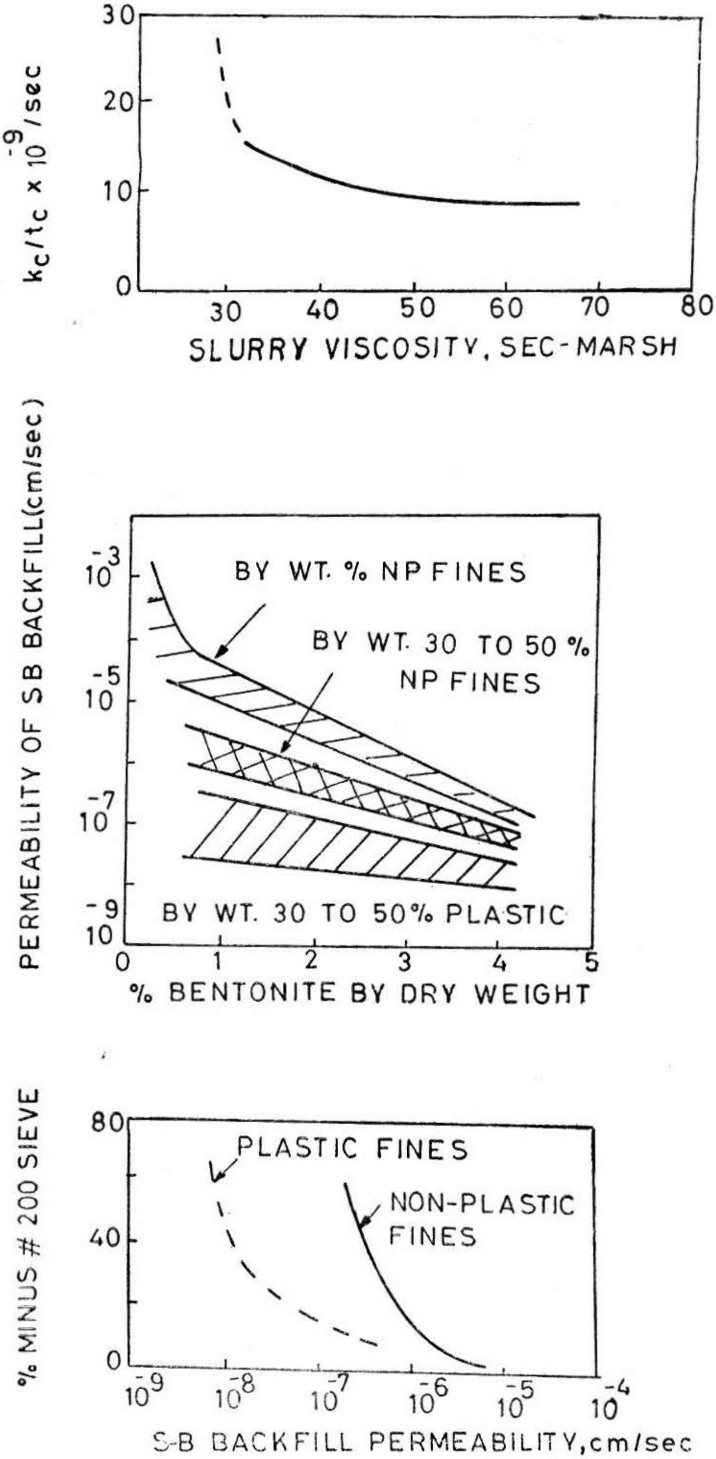

FIGURE 4 **Relation of permeability with slurry viscosity, % Bentonite and Fines Content in *S-B* Backfill (D'Appolonia 1980)**

Conclusions

Slurry cut-off walls are getting acceptance in wide variety of applications such as dewatering, pollution control etc. To construct the slurry cut-off wall, a trench is excavated and backfilled either with *S-B* slurry or *C-B* slurry. Both *S-B* slurry wall and *C-B* slurry wall have relative merits and demerits. However, both performs the basic functions i.e. formation of durable, flexible and impermeable walls. When designing a slurry cut-off wall, its functions, anticipated loading and other constraints should be taken into account.

In cases of chemical and industrial waste isolation using present state-of-the-art, permanent cut-off walls have been constructed which are resistant to degradation by waste material and have permeability in order of 10^{-8} cm/sec. or less.

The long term performance of slurry wall depends on the selection of backfill materials and construction quality control. Generally plastic fines give better performance over non-plastic fines and granular materials.

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Influence of the In-State Medium Properties on the Pressure Distribution Problems

Banabihari Misra

(*Indian Geotechical Journal, Vol. 12, No. 4, October 1982 pp 245-270*)

This paper describes, (1) why the classical elastic approach fails to incorporate the elastic properties (E, G and ν) of the medium in the pressure distribution problems, (2) a mathematical support to the concentration index hypothesis and (3) highlights the influence of E, G and ν in this important and complex problem of stress transmission in materials.

From a brief review on past studies, it is first shown that the in-state medium properties like E, G and ν definitely influence the stress transmittal. If it has been found otherwise it obviously indicates the limitation of the model adopted. It is then shown that the material parameter ($E:G$) approach, while giving the necessary material support to the concentration index hypothesis, is also able to reflect simultaneously the influence of all the three mechanical properties of the medium.

In order to elucidate their influence on this problem, selected numerical results for different types of boundary reactions concerning the half-space and finite layers resting on both rough and/or smooth rigid base, are presented in a non-dimensional graphical form to supplement earlier works on material parameter approach which is based on the model $E:G>2(1+\nu)$. The proposed model gives an effective explanation of the divergences between the results of the existing theories and reality.

KEY WORDS : Clays, Deformation, Elasticity, Footings, Granular Material, Loads, Sands, Soft Ground, Stresses, Stress Transmission.

Sub-Sieve Particle Size Analysis By Different Methods

B.R. Malhotra and Deep Chandra

(*Indian Geotechnical Journal, Vol. 12, No. 4, October 1982, pp. 271-280*)

The present study describes a device called "Plummet Balance" used for sub-sieve particle size analysis and compares the results of particle size distribution obtained by this device for different types of soils with those obtained by Hydrometer and Pipette methods.

Particle size distribution test results on a variety of soils have shown that percentage values passing different fractions obtained by plummet balance are tangibly less thän the corresponding percentage values obtained by other two methods. When the concentration of the soil solution used for analysis is increased from 0.02 to 0.03 per cent in the case of plummet balance, it gives results which are proximate to those obtained by hydrometer and pipette methods.

On comparing the results obtained by the hydrometer and pipette methods, it is seen that hydrometer gives slightly higher percentage values of different fractions for clayey soils but in the case of silty and sandy soils, percentage values for different fractions are more or less the same. Further, it is observed that particle size analysis for soils with little clay content is to be done by hydrometer and pipette methods.

KEY WORDS : Activity Co-efficient, Clay, Coarse Materials, Concentration, Fractions, Hydrometer, Particle Size Analysis, Pipette Method, Plummet Balance, Sand, Silt, Soil Solution, Specific Gravity, Stoke's Law, Sub-Sieve.

Correlation of CBR with Density and Moisture Content

S.N. Doshi and H.R. Guirguis

(*Indian Geotechnical Journal, Vol. 12, No. 4, October 1982, pp. 281-287*)

To get representative CBR values with less effort, the results of extensive quality control laboratory tests are used to establish correlations of CBR with maximum dry density and optimum moisture content for Kuwaiti soils. The validity of the proposed prediction models has been confirmed by the actual CBR tests. The correlations are found to be reliable and useful for Kuwait. Limitations of the prediction models are discussed at considerable length.

KEY WORDS : Correlations, Density, Moisture content, Soil classification.

Recent Trends in Design and Construction of Slurry Trench Cut-off Walls

Umesh Dayal and A.K. Goel

(*Indian Geotechnical Journal, Vol. 12, No. 4, October 1982, pp. 288-300*)

Slurry cut-off walls are non-structural walls constructed underground to intercept and impede groundwater flow. Principal applications are dewatering, pollution control and seepage barriers in the foundation of structure, water retaining structures, chemical waste isolation etc. Commonly used types of backfill are soil bentonite and cement bentonite which are discussed in detail. Most important properties of the backfill are permeability, strength and compressibility of the completed walls. A permeability of 10^{-6} to 10^{-7} cm/sec. can be easily obtained. Design and quality control criteria are recommended. This paper briefly review the present state-of-the-art on slurry wall construction and design guidelines.

KEY WORDS : Bentonite, Cement-Bentonite, Clay, Compressibility, Dewatering, Diaphragm Wall, Filtrate, Fines, Permeability, Pollution, Seepage, Seepage-Barriers, Soil-Bentonite, Stability, Strength, Viscosity.

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All discussions submitted on the papers published in the Indian Geotechnical Journal should be thought provoking and contribute to the aspects covered in the papers. Mere clarifications on points covered in the papers will not be published and the discusser should directly correspond with the authors.

Three typed copies of discussion complete in all respects (as indicated in Guide to Authors) should be submitted for publication.

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