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The need for fabrics in hydraulic engineering
La nécessité des textiles en génie hydraulique

RESUME

La conception de dispositifs de drainage capables de protéger les ouvrages de génie civil des effets nuisibles de l'eau est une des tâches principales des ingénieurs constructeurs. Bien qu'il existe des systèmes de drainage qui donnent satisfaction et permettent la réalisation de nombreux projets, une absence de contrôle de la saturation, des forces d'écoulement, des sous-pressions et de l'érosion interne peut compromettre la sécurité et l'économie d'innombrables ouvrages.

On peut rencontrer pratiquement partout des exemples de dégâts causés par des eaux internes, par des percolations et par des infiltrations de surface non contrôlées. Des glissements catastrophiques comme celui de Vaiont et des ruptures d'ouvrages comme celle du barrage du Téton font les gros titres, mais les insidieuses et coûteuses dégradations dues à l'action de l'eau sur toutes sortes d'ouvrages tels que les routes ou les ouvrages hydrauliques du monde entier, peuvent passer pratiquement inaperçues.

Un drainage efficace des structures hydrauliques, ou de tout autre type de construction, ne peut être assuré dans la plupart des cas que par l'inclusion d'une ou plusieurs couches, ou zones, d'un matériau granulaire très perméable, à forte porosité, à granulométrie étroite (en général dans l'intervalle 6 mm - 25 mm), en raison du fait que les mélanges de sable et de gravier que l'on essaie souvent d'utiliser ne sont pratiquement d'aucun secours si des débits appréciables sont à évacuer. Lorsque des granulats à granulométrie ouverte sont utilisés pour le drainage, ils doivent être protégés de façon permanente par des filtres appropriés pour empêcher leur colmatage et l'érosion interne des sols fins voisins. Obtenir de bons filtres avec des granulats minéraux naturels peut être difficile dans de nombreux cas, et cette difficulté va croissant dans de nombreuses régions du monde où les ressources en granulats de bonne qualité s'amenuisent.

Les textiles filtrants modernes offrent un moyen efficace de combiner un produit industriel et un milieu granulaire perméable de bonne qualité pour réaliser des dispositifs de drainage extrêmement efficaces - et souvent au moindre coût. Ces produits font leur apparition à un moment tout-à-fait opportun. Etant profondément convaincu de l'importance d'un bon drainage, je suis extrêmement heureux que ce colloque attire ainsi avec insistance l'attention du monde entier sur le problème du drainage, et je crois vraiment que nous nous trouvons à un tournant historique du développement de la technique.

1. INTRODUCTION

Many kinds of engineering works can be damaged by water if the proper control measures are not provided (Barrett, 1966 , Cedergren, 1967, 1974 ; Federal Highway Administration, U.S.A., 1973 ; Ring, 1974 ; U.S. Army Corps of Engineers, CERL, 1974 ; etc...). One of the primary jobs of Civil Engineers therefore is to make sure that adequate drainage measures are provided to protect their projects from water damage. In a broad sense, most of the problems with water are of two basic kinds : (a) those caused by the building up of saturation levels, uplift pressures and buoyancy to the point where stability under both static and seismic conditions is greatly reduced, or heave is likely to occur, or (b) those caused by the movement of soil and erodible rock particles to unprotected exits, resulting in "piping" failures. In the first category are failures of natural earth slopes, slope failures of earth dams, levees, etc., railroad embankment failures caused by seepage or rainfall infiltration, highway and airfield pavements damaged from heavy traffic on water-logged sections, failures of retaining walls from trapped water, and the like; in the second category are undermined breakwaters and slope protection works, earth dams that fail by piping of fine soil or erodible rock through open seams, open-work gravel, gopher holes, shrinkage drying cracks, and other passageways, etc.

Hydraulic structures and other facilities that are subjected to groundwater, seepage, surface infiltration from rain or melting snow and ice, or any other sources of water, can be protected from water damage only when saturation is adequately controlled and the movement of soil or soft rock particles is prevented. Simple though these two requirements are, failure to fulfill them contributes to many of the serious instability problems and seepage failures of Civil Engineering works throughout the world. Imballances in permeability often lie beneath the problems of controlling saturation and uplift (water that gets <u>in</u> faster than it can get <u>out</u> is the cause of the problems), and I believe that the extreme variations that can be found in the permeabilities of foundations, embankment zones, etc. is often an underlying factor contributing to seepage problems. Some photos in Fig. 1 illustrate the variability of permeability. Those who work with projects having need for control over water should develop a great deal of knowledge and experience with the permeabil-

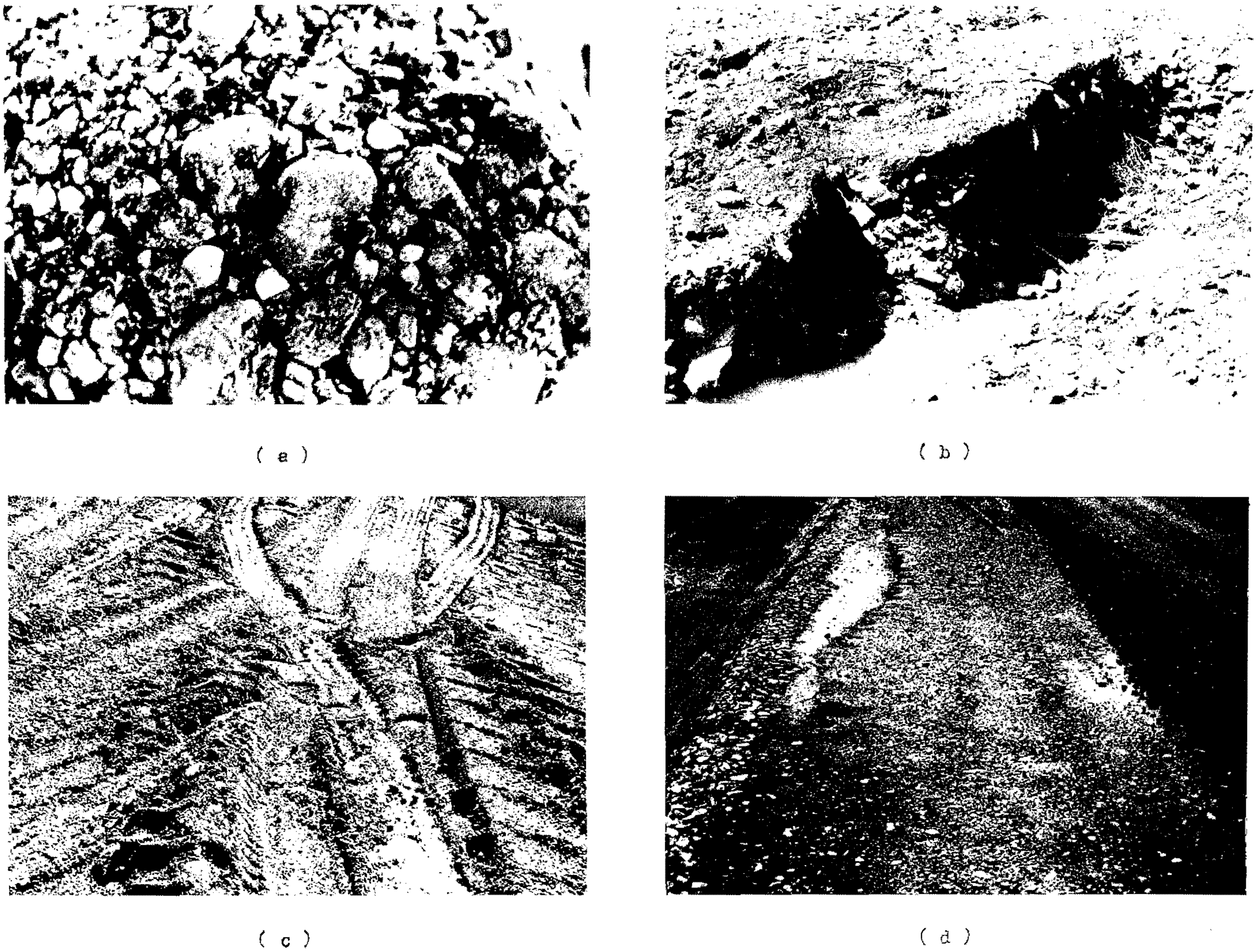

FIG. 1. Illustration of wide variability of permeability. (a) Coarse gravel in dam foundation, has k of 1 to 2 cm/sec. (b) Open-work gravel exposed in bottom of reservoir which cannot hold water, has k of more than 30 cm/sec. (c) Well graded sand and gravel in drain in dam, light areas are water standing on surface, k = 0.003 cm/sec. (d) Sand and gravel base course for a highway, water is still standing a week after a light shower, k = 0.0003 cm/sec. Total range represented is 100,000. Total range possible for earthen materials ranging from clay to coarse gravel is over 10 billion.

ities of all of the kinds of materials they will work with.

Many kinds of systems have been used for controlling seepage through and under hydraulic structures. Prominent among them are those that reduce or cut off the flows of water (impermeable linings, cutoffs, grout curtains, etc.); and methods that control the water by drainage. In many cases, both of these two fundamental control methods are employed; but in the majority of the cases, drainage systems provide the major control, with good quality mineral aggregates used alone or in combination with suitable filter fabrics.

2. *CRITERIA FOR FILTERS AND DRAINS.*

In this paper the requirements of good filters and drains are illustrated with reference to mineral aggregates. Tests and specifications for filter fabrics are described in a number of papers in Session 8 of this conference. In order to prevent "piping" problems, filters must be fine enough to hold erodible soils and rocks in place, but in order to freely remove all of the potentially damaging water from structures and their foundations and abutments, with only small amounts of head, drains must usually have high levels of permeability. These two diametrically opposing needs of filters and drains cause most of the serious problems. The well-known "Terzaghi" or "Bertram" piping criterion ($\underline{D}_{15}$ of a filter shall not exceed 4 or 5 times the $\underline{D}_{85}$ of a protected material) can provide a very high degree of protection against piping if it is satisfied in every part of a drainage system. Most designers of dams and other hydraulic structures have a good deal of confidence in this basic criterion. Frequently a secondary grading requirement that guarantees relatively smooth grain-size distribution curves for filter and drain layers is also imposed. In 1940 I conducted some piping experiments in which erodible soils were mixed with water to form slurries that were poured over filters meeting the "Terzaghi" criterion ($\underline{D}_{15}$ of filter not greater than 4 or 5 times the $\underline{D}_{85}$ of a protected soil). Even under these extremely severe test conditions, almost none of the soil went through the filters, with only a small amount of colloidal material washing through.

Another example of the sure benefits of good filters is a sand model I used for demonstrating the nature of flow of water in porous media. Non-cohesive sand was placed in the model over a coarse drainage layer of asphalt-stabilized pea gravel. To prevent piping, I hand-placed a thin filter (less than 2 cm thick) being careful not to allow any gaps to exist. Even though this model was taken several thousand miles (4000 to 5000 km) in the trunk of a car to 20 cities throughout California and Nevada and shipped by train from California to Washington, D. C. and I periodically poured water on the sand for testing purposes, hardly even a single grain of sand washed down through the filter. If no serious flaws or imperfections are permitted in even very thin filters meeting the basic piping criterion, piping is virtually impossible. But, if the criterion is not met everywhere, or filters are omitted in critical locations, piping failures are likely to occur, particularly when highly erodible soils are used in construction or exist in foundations of hydraulic structures.

A high level of filter protection can be provided for erodible soils and rocks by making use of drains constructed of blends of sand and gravel which meet the filter criterion previously discussed. But, aggregates which are fine enough to insure a high level of filter protection usually are too fine to have sufficient permeability to rapidly and effectively remove the water that reaches them. The conventional criterion for permeability of filters ($\underline{D}_{15}$ of filter must be at least 4 or 5 times the $\underline{D}_{15}$ of an adjacent protected soil) may not always guarantee sufficiently high permeability to insure good drainage. This criterion generally results in filters or drains that are several times (up to 20 or 25) more permeable than adjacent protected soils, and this is usually adequate when flow is basically <u>across</u> the thin dimension of a filter into a much higher permeability zone, as shown in Fig. 2. In such situations, the flow of water is occurring through relatively large areas of filter, and under relatively large hydraulic gradients, so if the filter (or transition) is just a little more permeable than the soil, relatively small head losses are needed to induce flow across the filter into a more permeable zone that finally removes the water. Even in these types of drainage design, permeability tests should

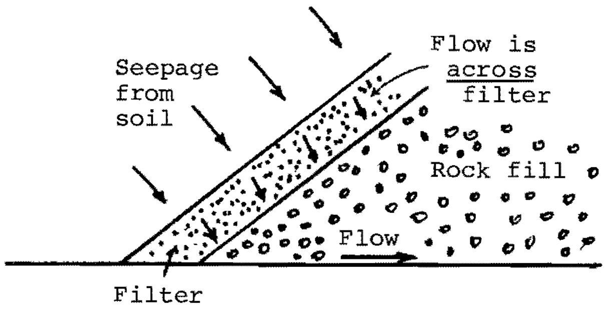

FIG. 2. An illustration of flow conditions requiring only moderate permeability in filters. Flow is <u>across</u> thin dimension of a filter.

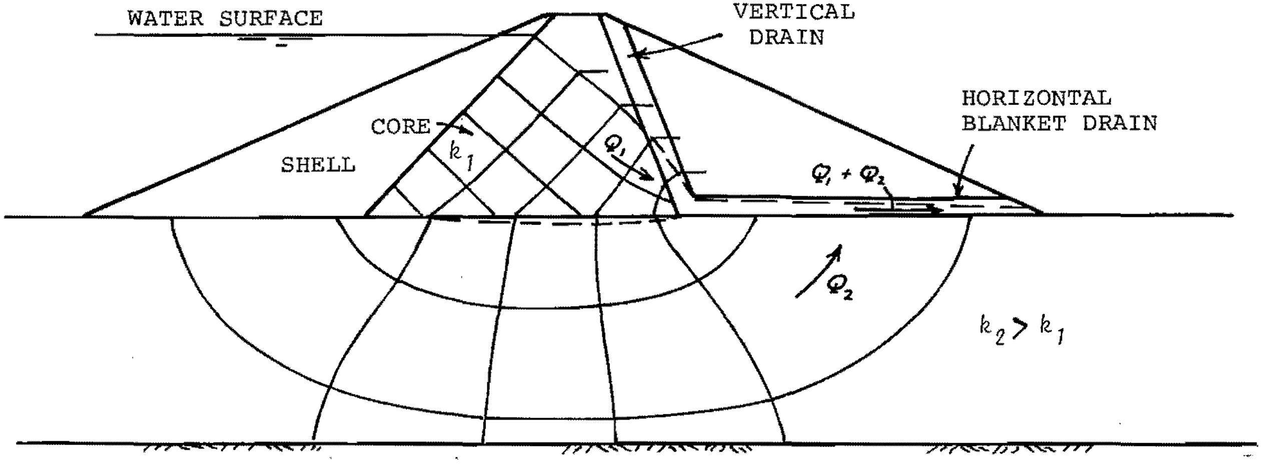

FIG. 3. Example of flow along the thin dimension of a drain. Seepage quantities Q_1 and Q_2 must be able to flow freely with only small head losses, in a horizontal direction in the horizontal blanket drain.

be made of both the protected soils and the filter materials, under compaction and density conditions expected in the prototype, to make sure that filters will be more permeable than soils being drained.

When the flow of water is along the thin dimension of a drain for a pavement, spillway slab, etc., or in an outlet blanket drain for a dam, as in Fig. 3, an additional criterion must be introduced to make sure that the drain will be capable of removing all of the water that reaches it with only a small amount of head loss in the drain. This can be assured only by analyzing the conducting elements of drains as conveyors or conductors in about the same way that sewer lines and water supply pipes are designed to carry calculated quantities of water. If the permeabilities of all formations and zones through which water flows toward a drain are known with reasonable certainty, Darcy's law and flow nets can be used for estimating the inflowing quantities of water and in developing drains that have sufficient transmissibility to remove all of the estimated inflows (multiplied by an adequate factor of safety such as 5, or 10, or 20, depending on the completeness of the explorations and tests). In those cases where the discharge capabilities of drains haven't been analyzed and taken into account in determining dimensions and permeabilities of drains, serious problems from uncontrolled saturation have been common occurrences.

Relatively simple calculations made with Darcy's law expressed in any of the following forms can be made to establish the minimum needs of drainage layers to insure sufficient water-removing capability to handle all of the estimated inflows:

$$k = \frac{Q}{iA} \qquad (1)$$

$$A = \frac{Q}{ki} \qquad (2)$$

$$kA = \frac{Q}{i} \qquad (3)$$

In these equations, $\underline{k}$ is the effective coefficient of permeability of a drain layer, $\underline{Q}$ is the quantity of water (per linear foot or meter of a drain), $\underline{i}$ is the average hydraulic gradient in the drain, and $\underline{A}$ is its cross-sectional area normal to the direction of flow in the drain. Equation 1 is used to calculate the required coefficient of permeability when the quantity of seepage, the hydraulic gradient, and the area (thickness) of the drain are known: Equation 2 is used to determine the required area (thickness) of a drain when its permeability has been assumed; and Eq. 3 is used to determine the product of $\underline{k}$ and $\underline{A}$ or drain transmissibility. If realistic estimates are made of the rates of flow that are likely to reach filters and drains, and taken into account in design, problems with inadequate discharge can be largely eliminated. When such determinations are not made, serious problems are very common. Examples of projects that had problems with piping or uncontrolled saturation are given in the following section.

3. EXAMPLES OF PROBLEMS WITH FILTERS AND DRAINS.

Piping Problems. *Example 1*. An earth dam with a maximum height of about 90 feet (27.4 m) was built on a loess foundation with compacted loess fill. A sloping drainage blanket 10 feet (3 m) wide on the downstream side of a cutoff trench, constructed with "selected" stream-bed gravels which contained boulders up to 6 in. (15 cm) diameter (as allowed by the specifications), was allowed to become badly segregated during placement with center-dump trucks, producing a zone of boulders in direct contact with the silt fill being used in building the dam. The ratio of D_{15} of the boulder zone to the D_{85} size of the silt was around 600:1, not 5:1 as required by the filter criterion previously discussed. During the first filling of the reservoir, the dam attendant noticed that the effluent from the drain pipe contained a large amount of soil, and he started saving samples in glass jars. A typical jar of about 1 liter volume, had several inches (about a centimeter) of sediment on the bottom after settling for about an hour. He notified his supervisors, who ordered the reservoir immediately lowered. This dam was saved because its reservoir could be quickly lowered. The cobble zone was grouted full of cement and a new drain was constructed.

Example 2. In this example, a small concrete diversion dam with earth wing dams retained an irrigation reservoir in central California. A fish ladder was constructed along one downstream abutment toe more than 25 years after the original construction. Silty sand and silt layers formed the foundation. Periodically over 10 years or so, the maintenance people had noticed gurgling noises under the fish ladder and had observed large holes forming in the area, and they had periodically placed one or more truck loads of coarse "drain rock" which graded from 2 in. (5 cm) to 3 in. (7.5 cm) in size. These people evidently thought they were doing the right thing, although they had obviously never heard of filter criteria! One night the dam failed very suddenly when water rushed through underground channels that evidently had been forming for years, and finally broke through to the reservoir side. This example demonstrates the importance of protecting coarse drains with suitable fine filters--either the right kind of mineral aggregate or a suitable fabric.

Problems with Uncontrolled Saturation. *Example 1*. Here, an earth dam with a height of about 200 feet (60 m) has a vertical "chimney" drain and a horizontal outlet drain, composed of three aggregate layers in each part. The dam is on moderately jointed, weathered sandstone. Outer "fine" filters of sandy gravel enclose inner "coarse" drain zones in both the vertical and horizontal parts of the drain. To allow the use of nearby sources of aggregate without extensive washing or screening the specifications permitted the "fine" filters to contain up to 5% of minus No. 200 (0.074 mm) material, and the "coarse" zones to contain up to 4% of minus No. 200 (0.074 mm) sizes. As a consequence, this expensive drain was unable to accept more than miniscule amounts of seepage, and large hydrostatic pressures built up under downstream parts of the dam, because the contractor found it cheaper to use the locally available aggregates with a minimum amount of processing, rather than producing materials of higher permeabilities. This example illustrates the kind of problem that often develops when no estimates have been made of discharge needs of drains, and low permeability materials are used. As a rule, the inner "coarse" parts of layered drains should contain no particles finer than about 1/2 in. (1.3 cm) or 1/4 in. (0.7 cm). The actual sizes used should provide the amount of permeability needed in individual cases.

Example 2. A chute spillway for a dam had a concrete lining with a bottom width of about 75 ft (23 m) and a length of around 200 ft (60 m). To prevent excessive uplift pressures from building up under the lining (it was founded on highly jointed rocks), a 12-in. thick (30 cm) drainage blanket of graded sand and gravel was put on the prepared foundation before pouring of the concrete. Slotted pipes were supposed to collect the water and feed it to outlets. Unfortunately, the specifications allowed the drainage material to contain 2% of minus No. 200 (0.074 mm) particle sizes, with the result that its permeability was too low to remove the incoming water when the reservoir was at a high level with no water flowing over the spillway. Serious uplifting of slabs occurred, and extensive repairs were required. Estimating the probable seepage quantities with Darcy's law or flow nets, as suggested in preceding paragraphs, so that drainage systems can be designed to remove all of the water that is anticipated, can usually avert this kind of problem.

4. CONCLUDING REMARKS.

In the above, I have shown some of the problems of obtaining good drainage and good filter protection with filters and drains composed entirely of mineral aggregates. Some of the problems illustrated were created in large measure by a lack of analysis of the discharge needs of drainage system components, and these problems usually can be overcome if reasonable estimates are made of the probable quantities of water that have to be removed and liberal factors of safety are allowed in the determination of the minimum required permeabilities of filter layers and water-removing elements of drains. Other problems, however, are enhanced by the difficulties of obtaining good quality, clean aggregates that have the required properties. As the supplies of high quality aggregates become even scarcer, it is likely that many of these problems will increase. Consequently filter fabrics, both woven and non-woven, will be looked to in the future more and more extensively as substitutes for high quality filter aggregates.

A recent American publication (Seemel, 1976) had the statement in relation to the synthetic fabrics, "Strength and inertness of these materials vary, but they are all generally rot-proof, mildew-proof, salt water-proof, and rodent-proof. They are, also not affected by hot or cold climates. Some are affected by alkalies, others by acidic materials, components of asphalt, or fuel oils. Most are seriously affected by long exposure to untra-violet components of sunlight. . . ." He also says, "For any tendency to deteriorate there are inevitably offsetting characteristics. Do not forget that the same is true of granular materials." While fabrics offer viable materials for many kinds of engineering drainage, there is need for longer-term records of good performance. Both filter protection and water flow capabilities of filters sufficient to meet the needs of individual projects must be retained over the expected life of a given works. Designers should make sure that a given material has the required properties and the minimum life expectancy for a given usage before allowing it to be incorporated in an important structure. Some design organizations (Calhoun, 1972) do not permit the use of fabrics in drains in the interiors of dams or in other situations where they would not be accessible in the event of a malfunction requiring removal and repair. As longer-term records of successful performance of projects with the fabrics become available to designers of hydraulic and other structures, one can presume that the fabrics will take on an ever increasing role in engineering drainage.

Careful construction practices that prevent the rupturing, tearing, or puncturing of the thin fabrics are, of course, essential to the insurance of the high levels of performance that are needed in dams and most other hydraulic engineering structures.

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