PRELOADING BY VACUUM: CURRENT PROSPECTS

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The concept of using atmospheric pressure to apply a precompression load for accelerating the consolidation of foundations for embankments constructed on soft clay soils was first described by Kjellman in 1952. The method, although theoretically sound, was impractical then because the plastic sheets that covered the sand filter deteriorated rapidly in field use, and consequently the vacuum could not be easily maintained. Recently, new plastic and fabric materials have been developed that promise to make the Kjellman vacuum preloading method practical. The materials are cheap, strong, and resistant to deterioration by sunlight and weather. Practical applications and several specific advantages of the vacuum method are described, and factors affecting the costs of highway and other preloading construction are given. Depending on the relative costs of the fill materials and the plastic membranes, the vacuum method can be significantly cheaper than conventional preloading using sand or gravel surcharge fills.

•IN 1952, Walter Kjellman (1), then director of the Swedish Geotechnical Institute, described a new method for using atmospheric pressure to apply temporary surcharge loadings for precompressing clays under highways and buildings. In the method, a plastic or rubber membrane is placed over a sand or gravel filter layer and sealed to the clay below the ground water table. Then a vacuum pump is connected, and the air is pumped out of the porous filter (Figure 1). The vacuum is maintained at the desired preload pressure, and a pressure difference of 0.6 or 0.7 atm (60 to 70 kPa), which is equivalent to about 16 ft (5 m) of sand fill at typical unit weights, is practical. Kjellman (2) intended the method to be used in conjunction with his paper drain wicks for accelerating the consolidation of clay soils, but it could be used with any type of deep drainage or simply to apply a surcharge without deep drainage.

The Kjellman method was tried at four test sites in Sweden in the late 1940s. At two of the sites, Kjellman paper drains were installed to a 16-ft (5-m) depth before a 0.9-ft-thick (0.3-m) sand fill was placed as the filter layer. At three sites, the membrane used was a 0.01-in.-thick (0.3-mm) polyvinyl chloride (PVC) plastic sheet, which unfortunately became brittle and developed leaks after just about 1 month. Apparently the deterioration of the plastic was caused by sunlight. A fourth test was tried using strips of rubberized fabric pasted together at the joints, and, although this material resisted deterioration better than PVC, it was not entirely satisfactory because of problems of sealing the joints and its high cost. No further tests were tried then, and as far as is known the method was never applied on actual construction projects in Sweden or anywhere else.

RECENT DEVELOPMENTS

During the past few years, skyrocketing construction costs have forced highway engineers to consider alternative solutions to many geotechnical problems that previously

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were rather easily solved by conventional means. For example, in the case of preloading and surcharge fills, the cost of fill materials increases about 10 percent per year or more because of increasing transportation costs, increasing cost of placing and then removing the surcharge materials, and, in some cases, the depletion or absence due to geologic factors of sand and gravel resources located near population centers. These developments and the fact that the most economic application of the precompression method is at sites where subsurface conditions are particularly poor and where the loadings are relatively light but cover large areas make the vacuum method increasingly attractive and economic.

In addition, since Kjellman's early experiments, significant advances have been made in the development of plastic materials and man-made fibers. Available today are vinyl and other types of plastic sheets that are often reinforced with woven polyamide (nylon) and other fabrics. These materials make an excellent air-tight membrane that is both strong, tough, and resistant to weathering and deterioration by sunlight and ideally suited for the vacuum preloading process. These materials are used for air-supported structures (e.g., warehouses and indoor sports halls), temporary environmental protection, reservoir liners, and the like. They are supplied in lightweight rolls that are easily handled in the field. Depending on the material, joints can readily be made by field welding by a hot air or a radio-frequency gun, field sewing, or special adhesive tapes. Costs, which depend on the thickness, strength, and weather resistance of the material, vary from 3.5 to about 25 cents/ft^2 (\$0.38 to \$2.70/m^2).

PRACTICAL APPLICATIONS

The geology and geotechnical properties at a given site must be suitable for using the precompression method, and the design and economics would govern whether or not the method would be used with deep drainage. Precompression theory and design, which are independent of how the preload is actually applied, have been covered in an excellent article by Johnson (3) and need no elaboration here. This section will describe some of the practical considerations associated with the application of the vacuum surcharge method itself using the new membrane materials.

Kjellman's sketch (Figure 1) showing the principal features is still applicable today. The filter layer should be a coarse sand or sand-gravel mixture about 12 to 20 in. thick (30 to 50 cm), and the membrane would be placed over it in sections, the joints welded, and the entire membrane sealed around the edges. If there is no dry crust and if the water table is close to the ground surface, then sealing can be made by simply piling some soil on the membrane around its periphery (Figure 2). If the dry crust is not too thick and the water table is high, a shallow ditch can be dug around the area, the membrane placed over the filter and down into the ditch, and then the ditch backfilled over the membrane (Figure 3).

Selection of the vacuum pump must consider the size of the area to be preloaded, the thickness of the filter, the desired magnitude of the preload, length of time it is to be applied, and presence of water. The size of the pump required is surprisingly small. For example, at two recent demonstrations of the method in Sweden, areas about 26 ft (8 m) square were effectively surcharged with about 0.8 atm (80 kPa) by a small pump driven by a ¼-hp (0.18-kW) motor. For larger areas, vacuum pumps with a 20-in.-thick (50-cm) filter are available that can easily maintain a vacuum of 0.6 to 0.7 atm (60 to 70 kPa) continuously for an area of 5,000 yd^2 (6000 m^2) [for example, a highway section 100 by 660 ft (30 by 200 m)]. To protect the pump, the vacuum line should be brought into a tank so that any water that collected could be periodically drawn off. To reduce pumping costs a vacuum switch could be connected to the pumps so that they would turn on when the vacuum reached, say, 0.6 atm (60 kPa) and would turn off at 0.8 atm (80 kPa).

Application of the preload in steps is generally unnecessary with the vacuum method because with typical preloads the chance of a bearing capacity failure of the surcharged area, or even a local slide, is greatly reduced. This is because there are no large shearing stresses on the base of the embankment that would occur with a granular fill

Figure 1. Principle of Kjellman's Swedish vacuum method.

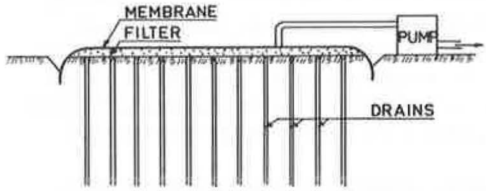


Figure 2. Kjellman method used where there is no dry crust and high water table.

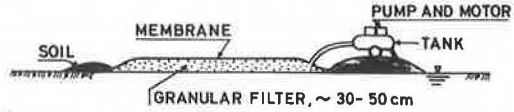
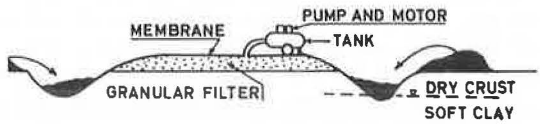


Figure 3. Kjellman method used where there is a thin, dry crust and high water table.



and that contribute to local instability. The presence of the vacuum at the surface of the clay also increases the efficiency of the surcharge because it provides an additional gradient over and above that caused by the increase in total stress due to the atmospheric pressure acting on the filter layer. With these two advantages of the vacuum method, it may be possible to greatly decrease the time required for preloading and at the same time avoid the expensive instrumentation, careful inspection, and delays that are often necessary with stage construction of large surcharge fills on weak foundations. An additional factor in favor of the vacuum method is that the time required for removal of the surcharge is negligible in comparison with the time required to remove and dispose of large masses of sand fill.

Another practical consideration is that the cost of the membrane material is usually so cheap that it probably is not worth the cost to remove it. In this case, it is suggested that initially the filter layer can be a minimum thickness, say 1 ft (0.3 cm), and, after preloading is complete, additional fill can be placed directly on the membrane to bring the embankment up to desired grade. The advantage of this is that, for very soft ground, the final height of the fill can be constructed after the soft soils are stabilized; of course the rest of the embankment need not be pervious material but can just as well be compacted earth fill. Depending on moisture considerations, such as frost action and swelling, an impervious membrane may be desirable in the fill; otherwise the membrane may be easily punctured with a harrow or other tool that is pulled behind a tractor. In addition, the membrane left in the fill can provide some reinforcement to the embankment, which is an added factor of safety.

COSTS

The many factors that enter into the design of preloading systems make cost comparisons between conventional surcharge fills and new techniques such as the vacuum method difficult. Cost of delays, cost and availability of suitable materials for the fill, and potential instability of the fill are but a few of the more important factors that must be considered in the design (3). Since the vacuum method has yet to be applied in any full-scale field situation, it is difficult to accurately estimate special costs associated directly with the method, for example, the cost of placement and sealing the joints and pumping costs. These costs must include a realistic consideration of any labor cost arising from operating union contracts and other labor regulations. In any event, as the cost of the surcharge materials increases relative to the cost of the membrane, the more economical the vacuum method becomes. For typical highway preloading situations, the difference can be 50 percent or more.

For the case of preloading large rectangular areas, water as an alternative surcharge method can be competitive but would generally be impractical for ordinary highway construction. Cost estimates were made for the project described by Tozzoli and York (4), and the vacuum method probably would have been somewhat cheaper than the water method. Certain problems experienced with the water method probably would not have occurred with the vacuum method, for example, wave erosion of the retention dikes and damage of the PVC liner by birds (some materials described earlier are strong enough to resist tearing by birds). In addition, the surcharge could have been instantly removed, but about 3 months were required to pump the water from the preloading ponds. Additional advantages of the vacuum method for this project include the elimination of the problem of low stability of the retention dikes and an increased consolidation gradient so that the time required for preloading with the vacuum method would have been significantly less.

PROSPECTS

The use of the Kjellman vacuum method for preloading highway and other fills is currently feasible, practical, and probably quite economic, especially as the cost of conventional surcharge materials increases. For typical highway preloading projects the cost difference could be 50 percent or more, depending on the cost of surcharge materials. Other advantages of the method include immediate rather than stage construction; instantaneous removal of the surcharge; avoidance of failures due to the reduction of the shearing stresses under the embankment; an increased gradient and consolidation rate; some additional reinforcement in the embankment; and, if desired, a free moisture barrier in the embankment.

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