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Geosynthetic Reinforced Slopes: Basics of Design and Some Projects

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ABSTRACT: Geosynthetic reinforced slopes became very popular worldwide during the last 15 years. This is a very efficient possibility to built "oversteep" slopes, say slopes, which would not be stable without multilayered horizontal reinforcement due to insufficient fill strength. The solution has financial, technical, ecological and landscape-related advantages. Meantime heights of up to 20 m and more are not rare, based on the possibilities of modern reinforcing geosynthetics. A short overview of design basics is given together with some interesting projects pointing out different aspects, solutions and experiences.

1 GENERAL

In many cases earth slopes have to be built steeper than allowed by the soil strength parameters. Over decades the problem has been solved by (usually vertical) retaining walls of different types and from different materials (stone masonry, concrete, reinforced concrete). At the beginning of the 60's the idea of reinforced earth was developed and introduced successfully by Henri Vidal using steel strips as soil reinforcement and vertical flat RC-facing elements. The horizontal strips provide additional retaining forces to keep even a vertical soil slope stable. The next step in the development of such retaining systems was to apply geosynthetic strips instead of steel because of durability and financial reasons, combining them with different facings.

The development continued introducing full width geosynthetic reinforcement instead of strips thus reinforcing the retained soil (fill) completely, and not only in single lines like in the case of strips. The latter solution proved to be very efficient over the years concerning stability, serviceability, and easiness of construction, durability and costs. Such a "full coverage" solution is by the way more redundant than a "pointed" strip solution, i.e. uncertainties, inhomogenities of the fill are less critical. The cost efficiency of geosynthetic-reinforced solutions in comparison to other systems is shown in Figure 1 (GRI 1998).

In many cases it is not necessary to build vertical or nearly vertical retaining walls. Very often the slope may have an inclination in the range of typically 50° to 80° to the horizontal to solve the "slope problem" for cuts and embankments. Such non-vertical but still very steep systems are usually called "reinforced slopes" (Fig. 2).

The main principle of the geosynthetic-reinforced retained soil mass remains valid. The geometry can be easily adapted to the geometry of the terrain and to the required geometry of a road or railroad trace. Because any inclination and curvature of the facing are possible, reinforced slopes can fit the landscape better than vertical walls.

In some codes and recommendations reinforced slopes are defined as systems with maximum 70° inclination of the facing to the horizontal. Steeper systems are then defined as "walls". Different design procedures are suggested for "slopes" and "walls". In the authors opinion there is no reason for such an artificial distinguishing. In discussions with colleagues worldwide over the years nobody was able to explain the reason for the 70° limit to the author. Additionally, the design results for a 68°-"slope" and for a 72°-"wall" can be quite different in terms of reinforcement

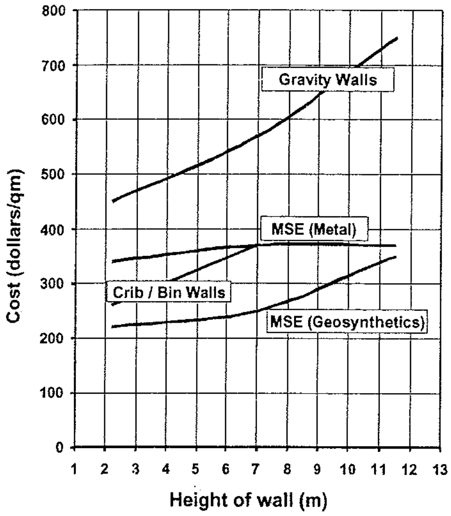


Figure 1: Comparison of costs for different retaining wall systems

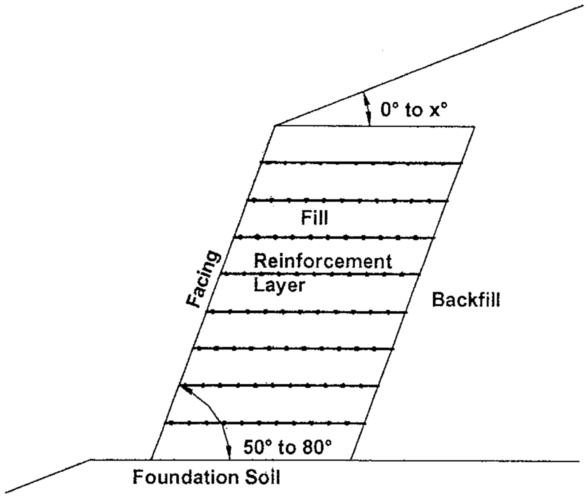


Figure 2: Typical scheme of a reinforced slope

layout, strength etc. based on the different calculation procedures suggested, but not on the geomechanical behaviour. The latter cannot be very different based only on a difference in facing inclination of only e.g. 4°, but the "jump" in formal design results will be nevertheless significant and not consistent with our common engineering sense. Consequently, in this paper a "reinforced slope" may have a facing inclination of up to 80°.

To the author's experience and opinion generally no difference should be made between "walls" and "slopes". Every "oversteep" reinforced system up to 90° inclination should undergo the same design procedures. This will be e.g. the case with the new draft of EBGEO (1997), which is under preparation.

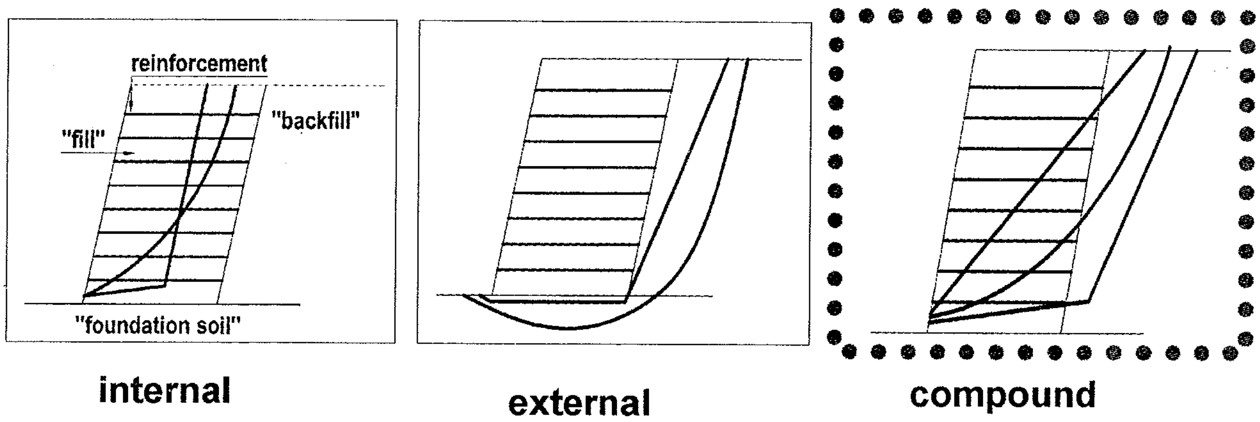
On the facing of reinforced slopes vegetation can be established providing a full integration of the engineering structure into the environment. Other types of facings are also possible as shown later in this paper. The systems are easy to build meeting the requirements for "common" earthworks, because earthwork technologies, equipment and experience are available worldwide, and quality assurance and control are well established. Because of the advantages mentioned reinforced slopes became very popular over the years especially in Europe and in some parts of Asia and South America with increasing tendency.

2 BASICS OF DESIGN AND SOME REMARKS

In the meantime the basics of design are explained in many recommendations and codes worldwide e.g. in BS 8006 (1995) and EBGEO (1997).

Generally, design calculations are based on the analyses of the ultimate limit state (ULS), i.e. failure of components or of the entire system, and on the analyses of the serviceability limit state (SLS), i.e. of deformations. The ULS-analysis is relatively simple, because well-known stability calculation procedures are used. Typically, these are the methods of Bishop with circular failure planes and of Janbu with polygonal ones. Both methods are explained in detail (but without reinforcement) e.g. in the well-established DIN 4084 (1981) or in its new draft DIN 4084 (2002).

The new components in the design are the retaining forces provided by the geosynthetic reinforcements. For the ULS-analysis the key issue is the design (allowed) strength of reinforcement F_d, kN/m. The design strength is strongly influenced by creep beside other factors; therefore low-creep reinforcement should be preferred. At any cross-point of reinforcement layer and possible failure plane F_d is applied as a retaining force. Note, that also the pull-



internal **external** **compound**

Figure 3: Typical possible modes of failure for geosynthetic-reinforced slopes

out forces from right to left $F_{\text{pull-out},1}$ and from left to right $F_{\text{pull-out},2}$ for this cross-point have to be calculated in order to avoid pull-out of reinforcement from the fill. Finally, the design value of the really effective retaining force in a given cross-point of failure plane and reinforcement is the lowest value of F_d, $F_{\text{pull-out},1}$ and $F_{\text{pull-out},2}$. Regarding the correct estimation of F_d see e.g. Alexiew (2004 in the same proceedings). Modern software performs the comparisons automatically for every reinforcement layer and every failure plane and considers the lowest value (e.g. "Huesker Stability").

Additionally, external stability calculations for failure planes of any kind outside/behind/below the reinforced "package" have to be performed as for a monolithic retaining wall (Fig. 3). More details can be found e.g. in BS 8006 (1995) and EBGEO (1997).

One important remark: based on the author's experience, very often the so called "compound" or "mixed" mode of failure is not being taken into consideration in stability analyses. In this mode the failure plane crosses both the reinforced zone and the unreinforced zone behind: it is neither the pure "internal" stability, nor the pure "external" one. Reinforced slope failures in a "compound" mode are known. Strictly speaking, the soil and its failure mechanism cannot make the difference between reinforced and unreinforced zone, between "internal" and "external" failure.

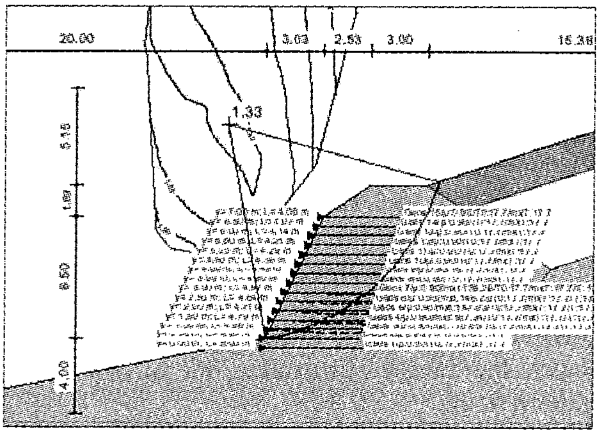


Figure 4: Example for stability calculation of compound mode using Bishop's method of circles acc. to DIN 4084

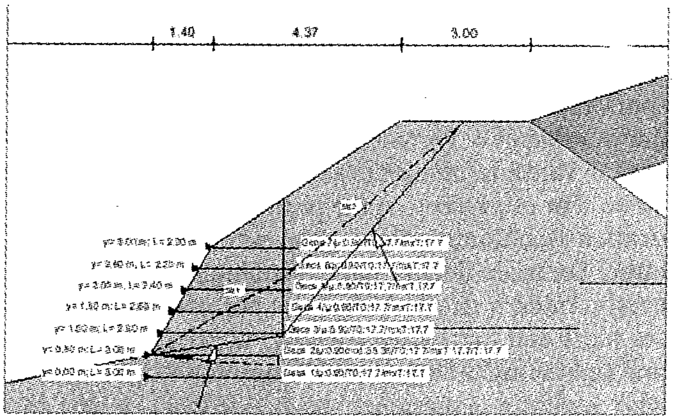


Figure 5: Example for stability calculations of compound mode using a polygonal failure plane acc. to DIN 4084

Such a formal difference is possible in a design code, but not in nature. That should be always kept in mind. Note the compound modes depicted in Figure 3!

To illustrate the design practice, in Figures 4 and 5 two different compound failure modes are displayed: using Bishop's method and using the block-sliding method, which is similar to Janbu's method. In both cases the stability calculations are performed using the program code "Huesker Stability" according to DIN 4084 (1981) with a global factor of safety. In that case the compound mode controlled the design, say the lengths and strengths of reinforcement.

Another specific mode of failure for geosynthetic reinforced walls and slopes is shown on Figure 6. If the coefficient of interaction between reinforcement and fill is not sufficient, the interface (contact surface) becomes a "weak" plane in which sliding can occur. The coefficient of interaction or bond is the relation of shear strength in the interface to the internal shear strength of fill. For optimized geosynthetic reinforcement the bond coefficient is equal to 1.0, therefore no "weak" plane exists, and the failure mode described does not control the design. For bond coefficients < 1.0 the mode has to be checked in design calculations. In any case, the information about reinforcement has to comprise the bond coefficients to different soils beside the reduction factors for design strength and the isochrones (Alexiew 2004).

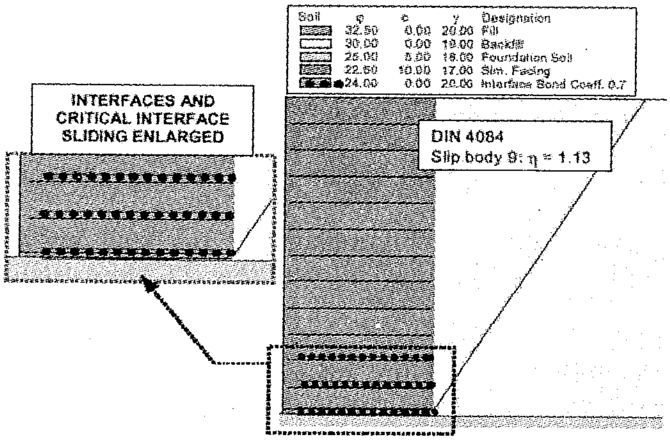


Figure 6: Possible critical sliding failure mode on an interface

Unfortunately, there are no sound analytical design procedures concerning the serviceability limit state (SLS). As help based on experience the additional creep strain in reinforcement after construction until the end of design life is being limited. Depending on the country, on the category of reinforced slope (e.g. below roads or railroads), on the safety philosophy, experience etc. the creep strain after end of construction until the end of the design life is usually limited to a value of 0.5% to 1.0%.

The first value is recommended for steeper, higher, heavily loaded slopes, the second one for slopes of less importance. For estimation of the post-construction creep strain under a given tensile force the design engineer needs the so-called isochrones of the geosynthetic reinforcement. These are graphs depicting the relation tensile force-strain-time. For more details and explanations see e.g. Alexiew (2004).

Recently, often numerical analyses are used for analysing the SLS. Such software is available in the market and becomes more and more user friendly, which has its dark sides, because the danger of mistakes due to short design times and tight schedules, and sometimes due to incompetence is relatively high.

In the author's experience such software tends to underestimate the tensile forces in the geosynthetic reinforcement. In any case, the output is very sensitive to the input parameters, and to the soil models (constitutive rules) chosen. To handle such program codes in an appropriate way requires a lot of experience. Nevertheless, it is a good tool to perform SLS-analyses: in any case better than simplified analytical approaches. For such numerical analyses the tensile modulus of reinforcement J is a key parameter. Its estimation is explained on Figure 7 based on isochrones (see above) because J is time-dependent due to creep. With time the reinforcement becomes quasi softer. The higher the propensity to creep, the lower becomes the tensile modulus J with time.

Consequently, it is important to use low-creep reinforcement also from the point of view of serviceability, and not only from the point of view of design strength for the ultimate state (see above).

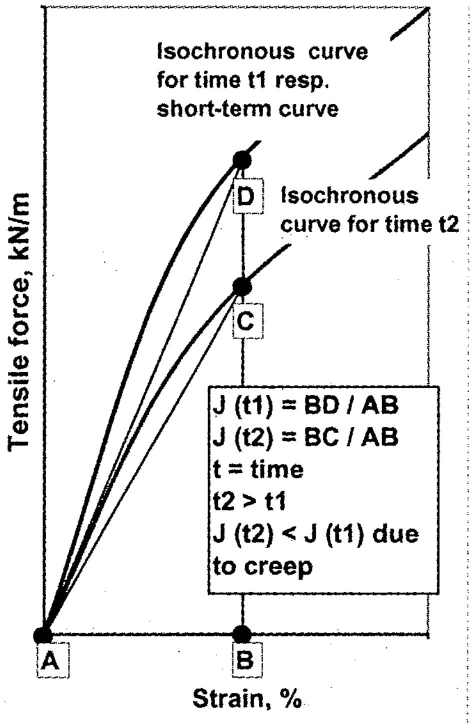


Figure 7: Estimation of the (time-dependent) tensile modulus of reinforcement J for the purpose of numerical serviceability analyses

3 SOME PROJECTS WITH REINFORCED SLOPES

Following a more or less chronological overview of some more interesting projects over the last years. They are selected to present some new solutions, or specific applications, or big heights, or new materials etc. Due to the limited space only few projects are shortly presented.

3.1 *Reconstruction and stabilization of a landslide (Project Steinmaderer Wand at Lech)*

In 1994 a huge landslide occurred in the Austrian Alps near the town of Lech just below a lift-station, endangering the entire building and blocking the road below. Due to financial, technical and environmental reasons a geogrid-reinforced slope was selected as the best solution for slope reconstruction (Fig. 8). Note the changing inclination of facing: the solution is very flexible and adaptive.

The slid soil mass was re-used as fill material. It was a mixed soil comprising mainly sands and gravels, but also a significant percentage of stones on the one hand and of silt on the other hand. Flexible low-creep geogrids were used applying a wrap-back scheme for the facing without any additional protection. The contractor used for the compaction of the facing zone removable wooden inclined formwork. Special attention was paid on soil compaction. A Proctor density of Dpr ≥ 0.98 was specified and achieved. Note, that quality of earthworks is very important while constructing reinforced slopes. It starts by the choice and specification of appropriate fill, including the prescribed density after compaction, and ends with a control on site. No geosynthetic reinforcement will help if the earthworks are of low quality.

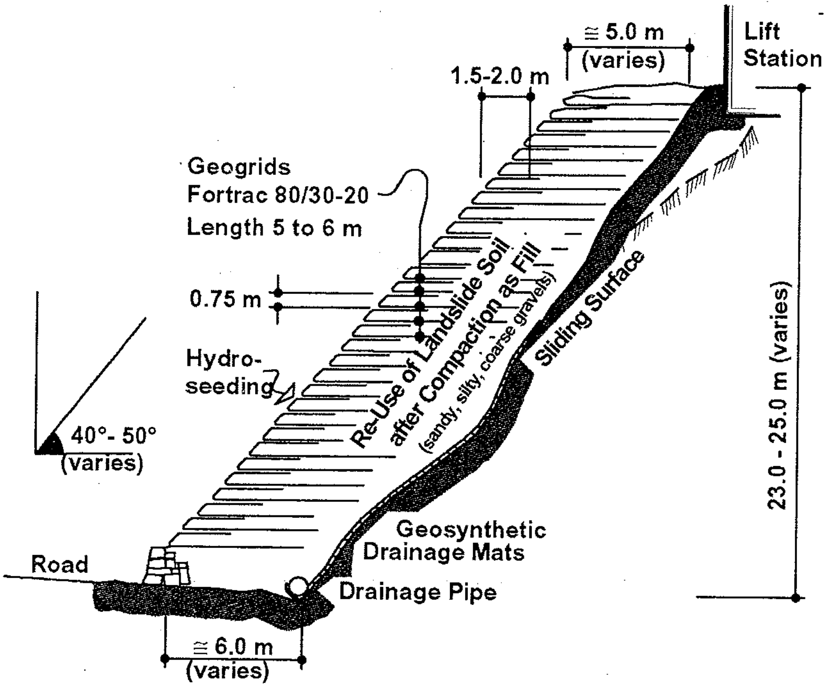


Figure 8: "Steinmaderer Wand": typical cross section

In the long-term, geotechnical (and not geosynthetic) problems will arise. Because the fill in that case was not really free draining, drainage mats were installed as shown in Figure 8. Finally, hydroseeding was applied at the facing. Figure 9 shows the slope just after completion, and Figure 10 one year later with the established vegetation. Construction time was less than three months. The performance of the reinforced slope meets all requirements until today (i.e. after 10 years).

Summary: Landslides can be reconstructed and stabilized using reinforced slope solutions. Re-use of slid soil mass as fill is an efficient option. Soil compaction and drainage are important. Low-creep geogrid reinforcement guarantees the long-term stability and serviceability.

3.2 *Widening of a road at a river (Project Federal Road B 277 at Dillheim, Germany)*

In 1996 the German Federal Road B 277 had to be widened near Dillheim due to increasing traffic intensity: one lane more had to be added (Fig. 11). On one side of the road there is a steep mountain slope, therefore the only possibility for widening was the side to the river Dill (Fig. 11).

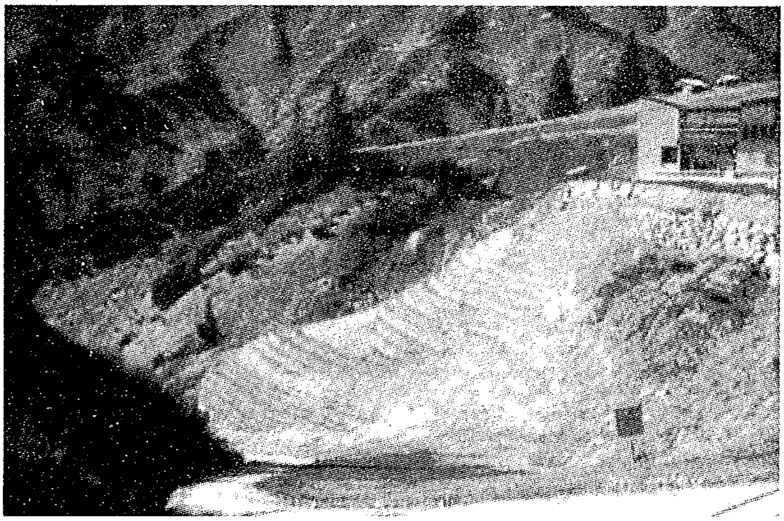


Figure 9: “Steinmaderer Wand”: reinforced slope just after completion; note the differing inclinations and slope shapes

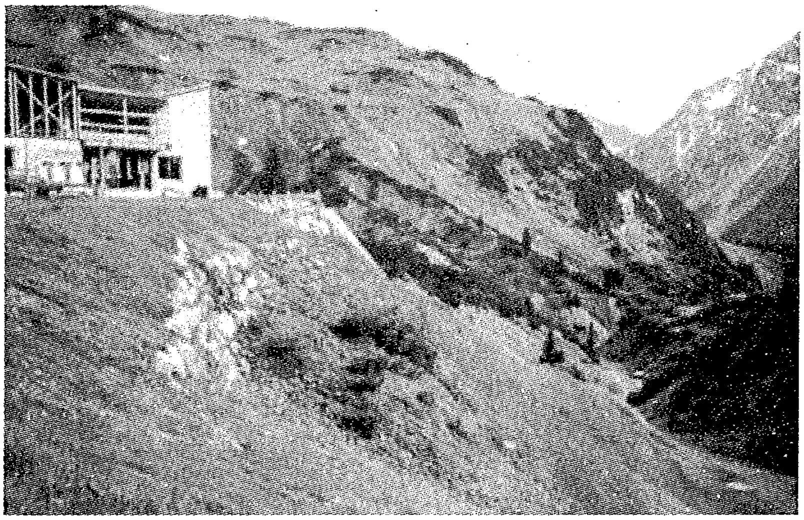


Figure 10: “Steinmaderer Wand”: one year later – the structure has become a part of natural landscape

The best solution was a geogrid-reinforced slope. Following issues were specific for that project: the water level in the river Dill can change quickly – the normal low water level is at the toe of slope and the high level is nearly at half of the slope height. Because of that the bottom half of the slope had to be constructed very quickly. Additionally, for that part a very coarse poorly graded crushed stone had to be used to allow a completely free drainage when the river level sinks quickly.

For the upper part “normal” sandy gravel could be used. The optimized design resulted in flexible low-creep geogrids of different lengths, a wrapped-back facing was chosen. The significant geogrid lengths in the bottom part installed as double layers were necessary due to the high driving hydraulic forces (steep phreatic line) in the case of quick decrease of water level in the river. For the bottom part of the facing an additional cover of heavy stones was foreseen because of the high velocity of river stream, and for the upper part grass vegetation. The contractor was able

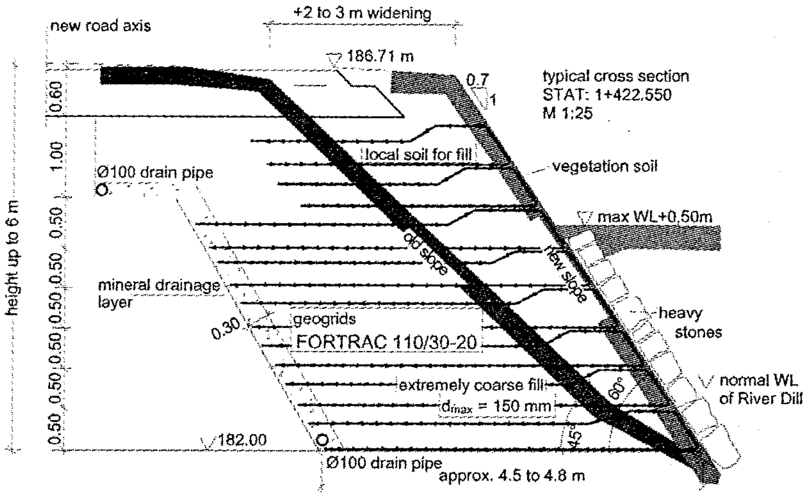


Figure 11 : “Federal Road B 227” – Typical cross-section differing inclinations and slope shapes

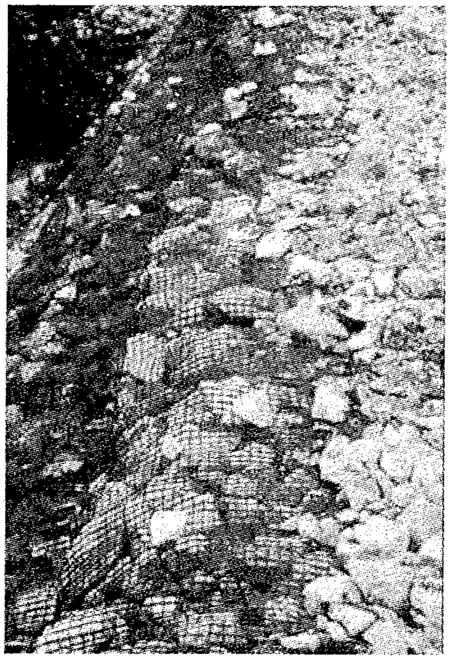


Figure 12 : “Federal Road B 227” – Extremely coarse fill confined by flexible geogrids

to build up the bottom part in only two weeks over a length of more than 200 meters. The flexible geogrids performed excellently despite the extreme coarseness of fill used (Fig. 12). The entire structure was completed without any problems, and performs from both mechanical and hydraulical point of view very well until today.

Summary: Geogrid reinforced slopes can be an appropriate solution for river slopes even under extreme hydraulic conditions. Appropriate flexible geogrids can be used in combination with extreme coarse fills. If required, reinforced slopes can be constructed very quickly.

3.3 *Steep reinforced slope from lime-stabilized local soil (Project "Logistic Centre Unterkaka", Germany)*

The project was developed in 1998. A large parking platform for heavy trucks had to be built (Fig. 13). The preferred solution incorporated the use of local soil (cohesive sandy silt and clay) after lime-stabilization, supported in front by a steep geogrid reinforced slope using the same stabilized soil as fill. Note the high surcharge of 33 kN/m². Due to the high alkalinity of lime- and cement-stabilized soils the geogrids used had not only to meet the usual requirements in regard of low-creep, but also to be highly chemical resistant and durable for a design life of 100 years. Flexible geogrids made of a new special polymer (so called "Fortrac® M"-series) were produced and applied to meet both requirements. A "green" facing was chosen using special long gabions filled with vegetation soil in front.

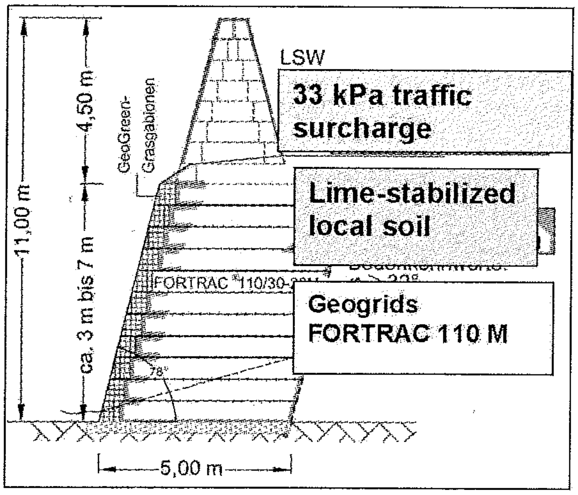


Figure 13: "Unterkaka": typical cross-section with lime-stabilized fill and highly chemical resistant geogrids

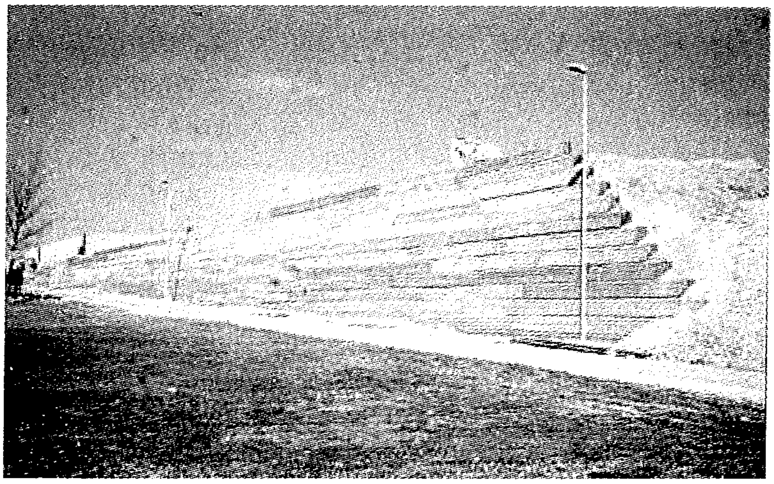


Figure 14 : "Unterkaka" – Reinforced slope and platform nearly completed

Homogenization and compaction of soil were executed very carefully. In Figure 14 the completed slope and platform are depicted. Until today the system performs well both in regard of bearing capacity and serviceability despite the heavy trucks driving on top.

Summary: Even high-cohesive local soils can be used as fill in reinforced slopes combining lime- or cement-stabilization with appropriate low-creep high-resistant geogrids. The geogrids used also proved to have a high bond coefficient to the fill. Reinforced slopes can bear very heavy loads successfully.

3.4 *A very high reinforced slope for a development platform (Project "Lobbe Holding" in Iserlohn, Germany)*

The project was developed in 2000, and designed and built in 2001 – 2002. A new high horizontal platform for a housing development is supported by a reinforced slope with a total height of up to 23.0 m being one of the highest structures of this type ever built (Fig. 15).

The total length of platform and slopes is more than 400 meters. The lower part of slope is vertical, the upper with an inclination of 80° to the horizontal. An old retaining wall was kept in place in the lower part due to architectonic reasons, but is insulated from any earth pressure by a void. One specific issue more was, that the investor had on disposal a large amount of recycled concrete, which had to be used as fill. Recycled building materials are (similar to lime- or cement-stabilized soils) of high alkaline aggressiveness, therefore special geogrids of high resistance had to be used as shown in Figure 15.

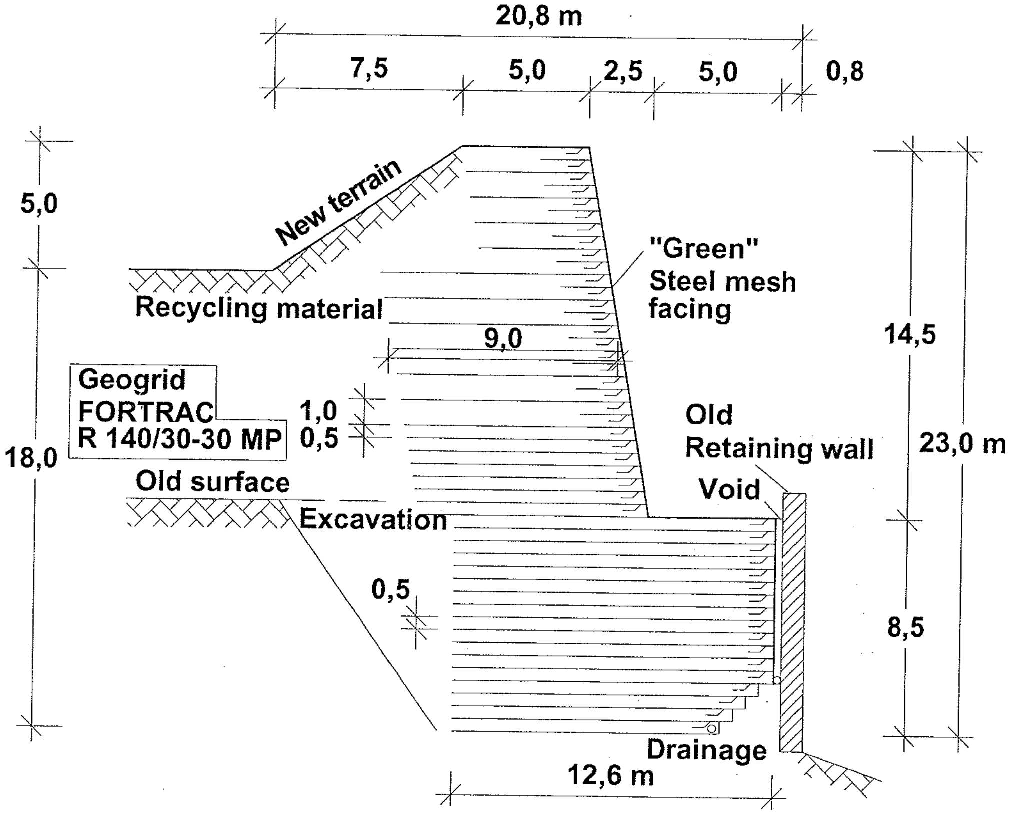


Figure 15: "Lobbe Holding": typical cross section

Vertical spacing and geogrid lengths vary over the height of slope. For the facing a wrapped-back scheme was chosen, using additionally in front steel grid as temporary formwork for compaction of the facing zone, and for protection against vandalism for the post-construction stage. Construction works lasted less than 2 years. An extensive measurement program was applied due to the unusual height of structure. The vertical and horizontal deformations of platform and facing over the last 2 years are in the range of 10 to 20 millimetres only with decreasing tendency, proving not only the stability but also the serviceability of that very high system. In Figure 16 an overview of the entire structure is depicted. Note the conical body, which is also built from the same fill and the same flexible geogrids, proving the flexibility of the technique.

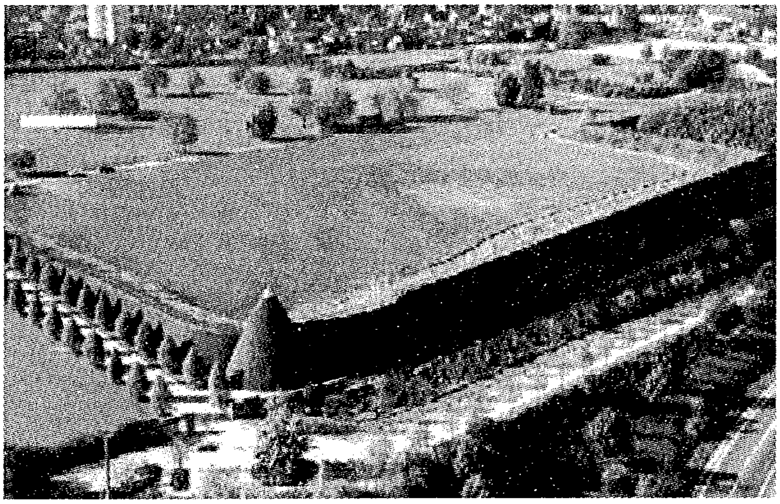


Figure 16: "Lobbe Holding": completed platform and reinforced slopes

Summary: Recycled materials can be successfully used as fill together with appropriate geogrids. Extremely high and steep reinforced slopes perform very well when based on appropriate design, control of earthworks and application of low-creep high-resistant geogrids.

3.5 *High reinforced slope for a motorway (Project "Etxegarate", Spain)*

A new motorway will connect Madrid in Spain to Paris in France. A part of the trace crosses a mountain region in the North-West of Spain. Because of that high embankments (some of them with "oversteep slopes") had to be constructed. Consultants and owner found out geogrids reinforced slopes to be the optimal solution. Such a system near Etxegaerate in Spain was designed and constructed in 2002-2003 with a height of 22 meters and facing inclination of 70° to the horizontal. It is to the author's knowledge the highest reinforced slope motorway embankment ever built. Following specific issues had to be considered: dynamic loads by the high-class motorway traffic, use of very coarse blasted non-sorted rock as fill (available from cuts and excavations on the trace), strict serviceability requirements. The optimized design included two unusual solutions: a big vertical spacing of 1.0 m between geogrid layers to ensure proper installation and compaction of the extremely coarse fill, and customized flexible geogrids with a wide squared mesh-size of 50 mm x 50 mm to ensure high interaction to the fill and to reduce the possible damage due to compaction of the blasted rock. In figure 17 a typical cross-section is shown together with a corresponding stability analyses according to Bishop and DIN 4084 (1981). Note, that only the lanes from Madrid to Paris are set on the embankment of 12.5 m width. The reverse direction was traced separately. A new type of facing was developed by the author and applied, consisting of rectangular steel grid creating a "stepped" facing. This concept made construction easier to meet the tight schedule despite the really big size of structure (total length of about 500 m).

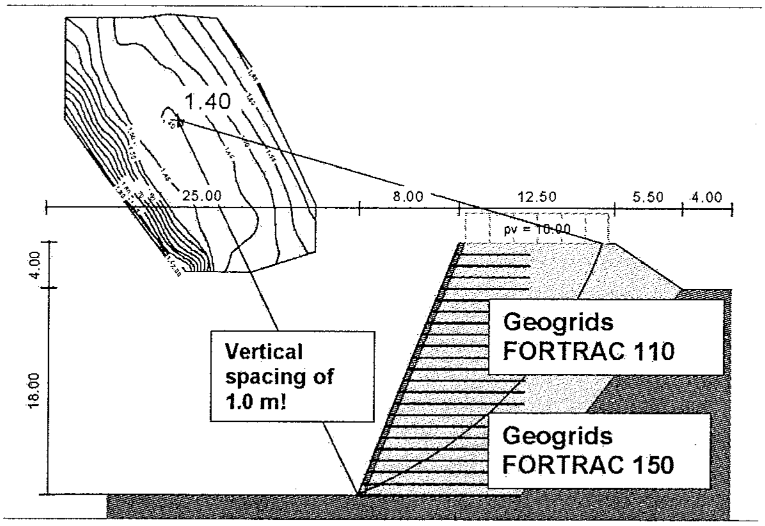


Figure 17: "Etxegarate": typical cross-section

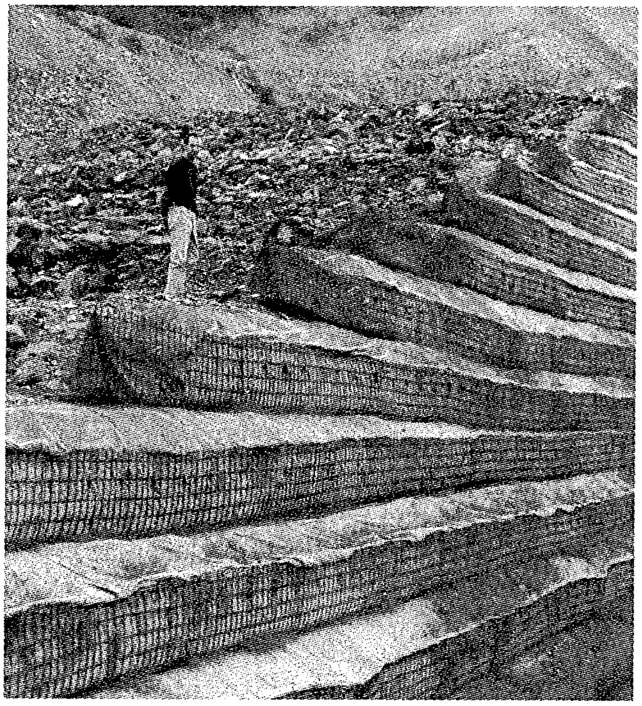


Figure 18: "Etxegarate": construction stage; note the big vertical spacings

Figure 18 shows a view of the stage of construction with the large geogrid spacing and blasted rock as fill. The completed structure can be seen in Figure 19.

Figure 19: "Etxegarate": structure just after completion

Summary: Really high road embankments can be built successfully with reinforced slopes. Even blasted rock can be used as fill material under the condition that appropriate customized geogrids with higher resistance to installation and compaction damage and customized mesh size to ensure interaction are applied. The system performs well even with big vertical spacing of 1.0 m between geogrid layers.

4 FINAL REMARKS

Geogrid-reinforced slopes proved to be an efficient solution for a wide range of geotechnical problems over the last ten years. They can be designed applying different facings and inclinations up to 90° to the horizontal, and with different curvatures in plan view. The inclination can even change for the same slope. Different solutions are available for the facing depending on safety, durability and environmental requirements. Standard earthwork procedures can be used, although quality assurance is important. A wide range of geogrids are available, therefore the design engineer can always find an optimal solution. Heights of up to 23 meters have been built successfully, and the structures perform well. Design should be carried out carefully, taking into account the specific design strength, long-term stress-strain behaviour and bond coefficient of the geosynthetics used.

REFERENCES

Alexiew, D. 2004. *Embankments on Soft Soils*. Geosynthetics – New Horizons, New Delhi. Asian Books.

British Standards Institution BS 8006. 1995. *Code of practice for strengthened / Reinforced soils and other fills*. London, BSI.

EBGEO 1997. *Empfehlungen für Bodenbewehrungen aus Geokunststoffen (Recommendations for Soil Reinforcements with Geosynthetics, in German)*. German Soc. Soil Mech. Geot. Eng. (ed.), DGGT, Ernst & Sohn.

Geosynthetic Research Institute GRI. 1998. *GRI Report No. 20* from June 18. GRI, Drexel University

DIN 4084. 1981. *Gelände- und Böschungsbruchberechnungen (Stability Calculations for Terrains and Slopes)*. DIN Berlin.

DIN 4084 2002-11 Draft. 2002. Gelände- und Böschungsbruchberechnungen (Stability Calculations for Terrains and Slopes). DIN Berlin

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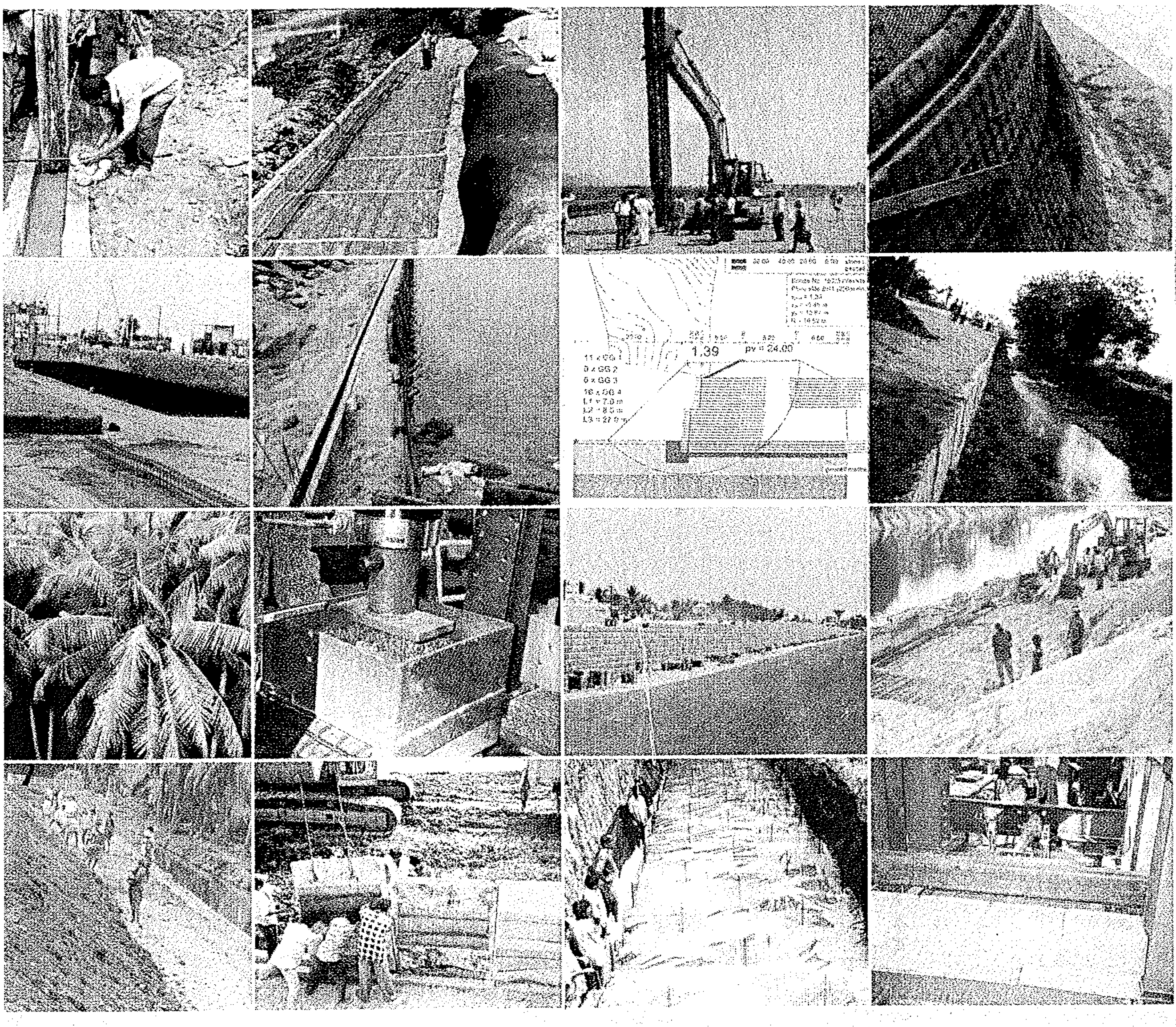

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FOREWORD

In view of the importance being given to rapid infrastructure development, be it roads and bridges, ports and waterways, or municipal and hazardous waste landfills, geosynthetics have found their way into civil engineering construction in India. Over the years, some experience has been gained by Indian engineers in the design and construction with geosynthetics. However, in view of the fact that there are various disciplines involved in the field of geosynthetics, viz., geotechnical engineering, environmental engineering, hydraulics, as well as the textile manufacturing and polymer technology, it is desirable to exchange views, consolidate the experiences and chalk out future directions.

Keeping this in view, a seminar-workshop GEOSYNTHETICS INDIA 2004 is organized by the Indian Geotechnical Society (Delhi Chapter) in association with Indian Institute of Technology, Delhi (Departments of Civil Engineering and Textile Technology), International Geosynthetics Society (India Chapter) and The Textile Association (Delhi Chapter). This will enable a close interaction amongst all those concerned with the technology of geosynthetics and its multitude of applications. This book comprises of the keynote papers, invited papers and contributed papers presented at the seminar-workshop on a wide spectrum of topics that are relevant to India. We wish to profusely thank the experts from around the world who have kindly contributed articles sharing their experiences. We are also indebted to the Indian experts and authors for their valuable contributions. The positive response received from the authors of the various papers at a very short notice needs special mention.

We wish to put on record our special appreciation to Mr. Murari Ratnam, Joint Director, Central Soils and Materials Research Station, New Delhi and Dr. R. Kuberan, Consultant, New Delhi for taking keen interest in reviewing the papers.

We are confident that this book, with its vast scope and detailed contents, will be a valuable addition to the State-of-the-Art on Geosynthetic Technology and will go a long way in promoting the rational use of geosynthetics in the country.

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