Disruption, innovation, and opportunity with reinforced soil structures

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Abstract. Reinforced soil is an area where amazing opportunity remains. Its failures have been embarrassing and disruptive, even catastrophic, for companies and governments. After reviewing design methods (i.e., limit, stiffness, and granular stability), this paper describes four areas of innovation and opportunity:

- Optimal Stiffness — fiberglass and aramid
- Stabilization of Poor Quality Fills — non-woven geosynthetics
- Friction Connections and Facing Pressure — steel grids
- Strips versus Sheets — geosynthetic strips

The two common construction types (i.e., steel strips, geosynthetic grids or sheets) represent only 25% or two out of eight possibilities discussed. This paper explains why the other six construction types, or 75%, are promising if not better.

1. Introduction

This paper discusses eight types of construction for reinforced soil structures. Table 1 reflects current products that span a broad range of material stiffness. Initial discussion involves the two most common types (✔): steel strips and geosynthetic grids or sheets. These represent 25% or two of eight.

| εR | grid/sheet | strip |
|----|------------|------|
| steel | 0.002 | ✔ |
| fiberglass or aramid | 0.03 | |
| woven geosynthetic | 0.10 | ✔ |
| non-woven geosynthetic | 0.30 | |

* εR = yield strain

Corrosion and deformation are associated with the two common types, and accordingly, two major disruptive failures from reinforced soil’s brief history are described. These are followed by innovations of design methods that enable eight opportunities and more.

In particular, non-woven geosynthetics promise an advantage with fine-grained soils in coastal defenses against rising sea levels, and they can be combined with concrete armor blocks.
2. Disruption
The two most common types of reinforced soil use steel strips or geosynthetic grids.

2.1. Steel Strips
One decade after the fundamental technique was developed by Vidal and Schlosser in France, it was deployed on six demonstration projects in the United States. These included a railroad overpass in Soda Springs, Idaho (USA), shown in figure 1(a). It was reinforced with steel strips. Despite a projected service life of 75 years, it failed after only 24 years [1].

The corrosion failure led to stricter code limits on pH, sulfates, and chlorides. Consequently, steel reinforcement is avoided near the sea.

2.2. Geosynthetic Grids
In 2009, a very high (75 m) soil structure was constructed of geosynthetic grids in order to support a runway extension at Yeager Airport, West Virginia (USA). Shown in figure 1(b), its 2015 collapse displaced a community of 130 people.

![Figure 1](image)

Figure 1. Failure of reinforced soil: (a) railroad overpass with steel strips, Soda Springs, Idaho (USA); (b) 75 m high runway extension with geosynthetic grids, Yeager Airport, West Virginia (USA).

It is generally agreed that the Yeager collapse was not caused by weak reinforcement or poor compaction [2]. Prior to its collapse, Wu and Pham identified an instability in such structures [3]. Wu-Pham instability was validated by the US Federal Highway Administration [4].

3. Innovation
Discussion of innovation requires an overview of granular stability, stiffness, and the limit method.

3.1. Limit Method
Retaining walls, which preceded reinforced soil, are designed with Rankine theory. This is a linear theory. The ratio of horizontal to vertical stress in the soil is a constant, that is, $\frac{\sigma_H}{\sigma_V} = K_a = \tan^2(45^\circ - \phi/2)$. The coefficient of active lateral earth pressure $K_a$ is constant because the soil’s angle of internal friction $\phi$ is assumed constant under drained conditions.

In reinforced soil, horizontal equilibrium of a soil layer is maintained by tension $T$ in the reinforcement. If $S$ is the layer’s thickness, then equilibrium requires that $T = \sigma_H S = K_a \sigma_V S = K_a q S$ where vertical stress is identified with surcharge $q$ on the soil layer. Again, this is linear theory, where
reinforcement tension $T$ is proportional to load or surcharge $q$. It follows that $q$ cannot exceed the upper bound on faced capacity,

$$\bar{q} = K_p T_f / S$$ (faced) (1)

where $T_f =$ tensile strength per unit width of the layer, $S =$ spacing or layer thickness, and $K_p = 1/K_A$ is the coefficient of passive lateral earth pressure for aggregates.

3.2. Stiffness

The ratio $K = \sigma_H / \sigma_V$ is not constant in reinforced soil. This was shown by Schlosser [5] with strain gauge measurements, figure 2(a), of the lateral stress ratio $K/K_A$. Schlosser’s measurements can be replicated by calculations, figure 2(b), based on Hooke’s law [6,7,8,9]. Schlosser’s chart reflects walls 6 meters high; therefore, calculation of stiffness curves for Schlosser-type diagrams requires normalization by the height or surcharge. Normalized, the horizontal axis becomes the load fraction,

$$\lambda \equiv q / \bar{q}$$ (definition) (2)

because load $q$ cannot exceed $\bar{q}$ of Equation (1).

Strain gauge data in figure 2(a) are consistent with grid-based calculations in figure 2(b). From an initial stiffness near $K_p/2$, values decrease as load increases. Steel strips are less stiff than steel grids. Stiffness $K/K_A$ is affected by extensibility $\varepsilon_R$, which is defined here as the reinforcement’s yield strain. For steel, it is 0.002. Table 1 lists other materials. Figure 2(b) is a Schlosser diagram that plots stiffness curves, i.e., $K/K_A$ versus $\lambda$, for common construction with grids or sheets where only material extensibility $\varepsilon_R$ varies. In figure 2(b),

- because $K/K_A > 1$ for steel, capacity is reduced
- because $K/K_A < 1$ for geosynthetics at service load, settlement occurs
- because $K/K_A = 1$ for fiberglass at service load, there is neither settlement nor lost capacity

![Figure 2](image-url)
Validation of figure 2(b) is provided by data like that of the steel strip wall [10] shown in figure 3(a). The dashed line of the calculated stiffness passes through the top of the cloud of datapoints. Slightly above these is the stiffness specified by highway code in America. Corresponding to reinforcement rupture, the limit state is the solid line at the right. The limit state is reduced by stiffness when \( K/K_A > 1 \). In figure 3(a), the limit state coincides with capacity. The soil structure was loaded with large weights of equal mass, and failure occurred as another weight was being placed.

3.3. Stability
Equation (1) is the faced capacity of a soil structure reinforced with geosynthetics. Wu and Pham [3] investigated the unfaced capacity \( q \) of such a structure. The bar is placed beneath \( q \) because unfaced capacity is less than faced capacity, which has an upper bar. For woven geosynthetic reinforcement, they found the ratio \( W \) between faced capacity \( \bar{q} \) and unfaced capacity,

\[
\frac{q}{\bar{q}} = W = \left[ 0.7^{S/D} \right] q
\]

(W for woven geosynthetics) (3)

where \( S = \) spacing or layer thickness and \( D = \) diameter of uniform aggregate. When not uniform, \( D \) is \( D_{\text{max}} \) or \( D_{\text{85}} \) because the granular stability factor \( W \) reflects blockage by the largest particles.

In Washington, the Federal Highway Administration tested four pairs of piers, 1m x 1m x 2m high [4]. In each pair, one was faced, and the other was unfaced because its facing blocks were removed after construction. Each pier was loaded to failure. Ratios of unfaced over faced capacity are plotted in figure 3(b) for geosynthetic sheets. These provide strong validation because the ratio of two measurements requires neither data reduction nor knowledge of material properties.

Figure 3. Validation of calculations with test data: (a) stiffness \( K/K_A \) versus load for steel strip wall at Vicksburg, USA; (b) stability \( W = \frac{q}{\bar{q}} \) versus \( S/D \), which is spacing over particle diameter.
4. Further Innovation

Although Wu-Pham stability applies to woven geosynthetics, it can be generalized to other materials. Furthermore, it can be generalized to strips or straps of such materials. Strap connotes a heavy strip.

4.1. Stability with Other Materials

The work of Sokolovsky [11] is the basis for a generalized approach to stability for reinforced soil. Terzaghi [12] used approximations in order to extend the plasticity theory of Prandtl [13] to Mohr-Coulomb materials. Sokolovsky put mathematical rigor into Terzaghi’s bearing capacity theory.

Although bearing capacity in figure 4(a) uses Sokolovsky’s solution with normal stress, reinforced soil stability in figure 4(b) uses shear stress.

![Figure 4](image)

**Figure 4.** Sokolovsky’s solution with (a) normal stress gives Terzaghi bearing capacity and with (b) shear stress gives stable capacity for unfaced reinforced soil.

When generalized [14,15], the Wu-Pham stability equation becomes $W = \exp(-\mu K S/D)$. Because $W = \lambda$ or load where instability first occurs, this equation’s inverse is

$$\frac{K}{K_A} = \frac{-\ln \lambda}{(\mu K_A)(S/D)}$$

where $\mu = \tan \phi$ is the coefficient of friction associated with the soil’s friction angle. Figure 5(a) plots the curve for $S/D = 8$, and as predicted by Wu-Pham’s equation (3) for woven geosynthetics, an unfaced pier will collapse when load fraction $\lambda = 0.62$.

![Figure 5](image)

**Figure 5.** Stability plots on Schlosser diagrams: (a) stability for $S/D = 8$; (b) stability for $S/D = 60$, which matches the stiffness at service load of non-woven geosynthetic when $\varepsilon_R = 0.50$.

Figure 5(b) plots the granular stability curve for $S/D = 60$ and extensibility $\varepsilon_R = 0.50$. Extensibilities greater than 0.15 are associated with non-woven fabrics that are typically used for filters. However, $T_f = 35$ kN/m and $S = 0.1$ m provides the same faced capacity as $T_f = 70$ kN/m and $S = 0.2$ m. In figure
(b), the granular stability and stiffness curves coincide throughout a wide range of service loads. This suggests that an unfaced vertical pier could be constructed and tested with $S = 0.1$ m and $D_{\text{max}} = 1.7$ mm. According to figure 6(a), high capacity structures can be designed with a variety of in-situ fills; however, designs must accommodate settlement that accompanies extensibility. Compaction and pre-loading strategies can shift settlement forward in time from the service phase to the construction phase, where it is easily accommodated and hidden.

In seawalls, the armor requires granular stability of the core, which usually involves coarse aggregates [16]. Although effective stress $\phi'$ is applicable in the core, non-woven geosynthetics could stabilize material that is readily available in the seabed and eliminate the need for immense quarries!

4.2. Strip Reinforcement
For strips and straps, the coverage ratio is $R_c = \frac{b}{S_H}$, where $b$ is strip width and $S_H$ is horizontal spacing. When horizontal and vertical spacings are equal ($S_H = S_V$), equation (4) for sheets and grids becomes equation (5) for strips and straps,

$$\frac{K}{K_A} = -\ln\left(\frac{\sqrt{R_c} \sqrt{\lambda}}{(\mu K_A)(S / D)}\right)$$

Therefore, granular stability improves when both $R_c$ and $S/D$ decrease. Elmagre [9] validated equation (5) in laboratory tests of unfaced structures reinforced with geosynthetic sheets and strips.

Stability affects stiffness. Stable soil structures are stiffer than unstable ones, and this effect is greatly amplified by strips. That is, a stable structure with strips is stiffer than the corresponding structure with grids; on the other hand, an unstable structure with strips is less stiff than the corresponding structure with grids [9].

5. Opportunity
Opportunities are discussed in the order of decreasing stiffness: steel grids, fiberglass, geosynthetic strips, and non-woven geosynthetics.

5.1. Steel Grids
As Section 4.2 indicates, soil structures with steel strips quickly lose their initial stiffness because of instability. In contrast, soil structures with steel grids remain stable longer with increasing lead, and at
service load, facing pressure places enormous tension on connectors. Figure 7(a) shows a steel-grid-reinforced abutment in Kelowna, British Columbia (Canada) whose faulty facing connectors failed during construction [17].

With steel grids, friction connections provide an effective alternative to rigid connectors. Gabion facing can slide with respect to the steel grid of welded wire fabric in figure 7(b). Sliding tiny distances relieves facing pressure greatly.

![Figure 7](image)

**Figure 7.** Steel grids cause enormous facing pressure: (a) connectors must be robust enough to avoid failure or (b) must be replaced by friction connections that slide slightly and relieve facing pressure.

### 5.2. Fiberglass or Aramid

Because aramid is much stiffer than common polymers, it is grouped here with fiberglass, not geosynthetics. Figure 2(b) shows that these materials are stiffer than most aggregates under service load. Consequently, they suppress deformation caused by soil expansion or freeze-thaw cycles. Unlike steel, they do not reduce capacity due to excessive stiffness. For these reasons, fiberglass and aramid might be considered *optimal* for stabilizing aggregates.

In Denver (USA), fiberglass grids are used to suppress expansive soil for the commuter railbed in figure 8(a). Denver also finds that it prevents freeze-thaw cracking of asphalt as in figure 8(b).

![Figure 8](image)

**Figure 8.** In Denver (USA), fiberglass grids (a) suppress expansive soil in a commuter railbed and (b) prevent unwanted freeze-thaw cracks in asphalt.

### 5.3. Geosynthetic Strips

Geosynthetic strips are prohibited by the highway code in North America [18]. Although strength is reduced by the coverage ratio $R_c$, Equation (5) shows that stiffness and stability are increased when $S/D$ is controlled. Defying intuition, geosynthetic strips can significantly reduce deformation experienced with geosynthetic sheets. Figure 9(a) shows a tall structure reinforced with geosynthetic strips in Oman [19].

Another benefit is that geosynthetic strips facilitate the use of facing panels, shown in figure 9(b).
Figure 9. Geosynthetic strips (a) provide soil reinforcement for a large structure in Oman and (b) facilitate the use of panels.

5.4. Non-woven Geosynthetics

Figure 6(a) indicates that fine-grained soils can be stabilized with non-woven geosynthetics. In figure 10(b), YouTube [20] provides persuasive validation by an engineer, who uses reinforced sand to support a car. In practice, figure 10(a), Tatsuoka [21] used non-woven geosynthetics with fine-grained soils on Japan Railway.

Non-woven geosynthetics promise an advantage with fine-grained soils in defense against rising sea levels, and it can be combined with concrete armor blocks.

Figure 10. Non-woven geosynthetics were used with fine-grained soils by Japan Railway. On YouTube, an engineer provides informal but persuasive validation.

6. Conclusion

Within geotechnical engineering, reinforced soil is an area where amazing opportunity remains. Lack of research has led to failures that are sometimes catastrophic but always embarrassing to companies and governments. This paper briefly describes four innovations and opportunities:

- Optimal Stiffness (e.g., fiberglass and aramid)
- Stabilization of Poor Quality Fills (e.g., non-woven geosynthetics)
- Friction Connections and Facing Pressure (e.g., steel grids)
- Strips versus Sheets, (e.g., geosynthetic strips)
The two common construction types (i.e., steel strips, geosynthetic grids or sheets) represent only 25% or two out of eight obvious possibilities.

Table 2. Types of Reinforced Soil Construction

| ε_r | grid-sheet | strip |
|-----|------------|-------|
| steel | 0.002 | ✔ | ✔ |
| fiberglass or aramid | 0.03 | ✔ | ✔ |
| woven geosynthetic | 0.10 | ✔ | ✔ |
| non-woven geosynthetic | 0.30 | ✔ | ✔ |

*ε_r = yield strain

This paper shows that the other six types of Table 2 are promising, if not better. Furthermore, non-woven geosynthetics promise an advantage with fine-grained soils in defense against rising sea levels, and it can be combined with concrete armor blocks.

Cost could be an impediment, but the more immediate constraint might be vertically integrated design frameworks that artificially limit an engineer’s horizon of possibilities.

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