Landmarks in Earth Reinforcement, Ochiai et al. (eds),
© 2001 Swets & Zeitlinger, ISBN 90 2651 863 3

Flexible facing systems for reinforced soil wall structures – characteristics and performance

Malcolm Boyd
Jabiru Technique Pty Ltd, Sydney, Australia

Pierre Segrestin
Freyssinet Internationale, Paris, France

ABSTRACT: Facing systems provide a cladding, or skin, to a reinforced soil structure and as such need to be flexible. They need to deform in three directions – transversally, vertically and longitudinally. The ability to deform without loss of function (flexibility) is important to the overall behaviour of the system. It effects the mobilisation of stress in the earth structure and its deformation characteristics. A preliminary quantitative comparison of flexibility highlights the differences between current panel and block systems and quantitative flexibility characteristics are proposed.

1 INTRODUCTION

Facing systems for reinforced soil structures provide a cladding, or skin, to the earth structure itself. They are required to retain the earth between the reinforcing layers, and to respond to the behaviour of the earth to which they are attached. Facing may be either hard (eg concrete) or deformable (eg metallic sheet or mesh) or soft (eg geosynthetic or woven wire sheets). Hard and deformable facing systems also serve as a formwork against which the earth backfill is placed and a template for layout of the reinforcement.

Flexibility is a critical characteristic of the facing system as it influences the behaviour of reinforced soil structures both during construction (mobilisation of stress) and after construction (modification of stress). Increased connection loads can result from differential settlement of the earth and facing with vertically stiff facing systems. Stress redistribution, facing degradation and loss of connection integrity can result from differential settlements along the wall due to construction or foundation variations with longitudinally stiff facing systems influenced by facing unit shape, configuration and joint characteristics.

2 FLEXIBILITY CHARACTERISTICS

Flexibility is the ability to deform. The facing system of a reinforced soil structure may have to deform in three directions:

1) Transversally, where the facing deforms perpendicularly to its surface (⇔)
2) Vertically, where the facing is compressed (⇕) in unison with the backfill
3) Longitudinally, where the facing rotates, or translates, to withstand differential settlements (↻).

The measurement of deformation is usually defined as in Figures 1, 2 and 3. For transversal deformation it may be defined in absolute terms as a local variation from a designed surface profile, D (Fig.1), or as a lateral deformation ratio, D/H. Vertical deformation may be expressed as a compression ratio, $\Delta H/H$ (Fig.2). Longitudinal deformation may be expressed as a differential settlement ratio, $\Delta S/\Delta L$ (Fig.3).

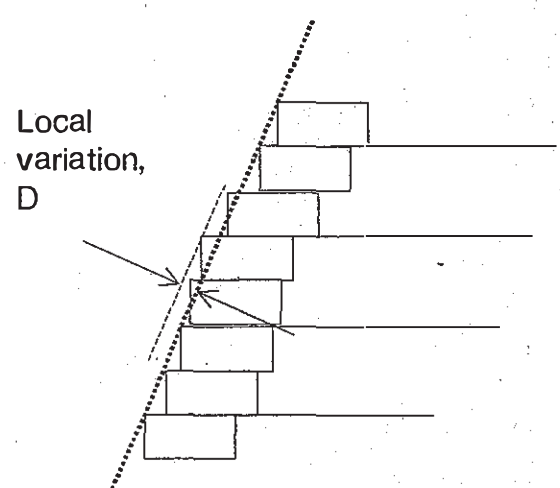

Figure 1. Transversal deformation (section).

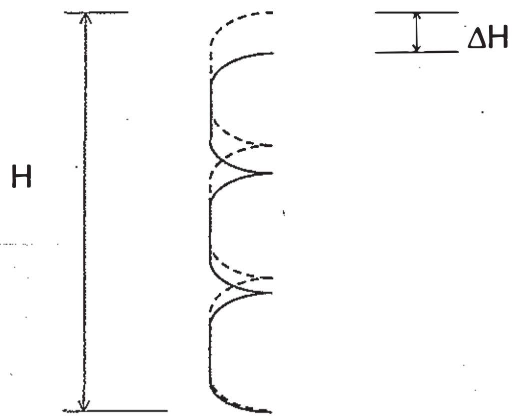

Figure 2. Vertical deformation (section).

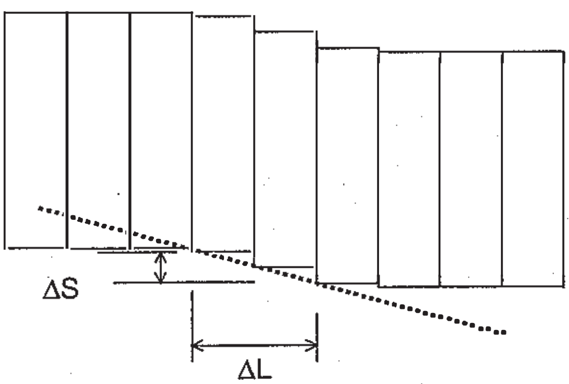

Figure 3. Longitudinal deformation (elevation).

2.1 *Transversal flexibility*

Transversal flexibility is obtained from the following

- deformability of the material itself (geosynthetic sheets or grids, steel wire mesh), or
- shape of the facing units (semi-elliptical steel units), or
- joints placed at regular horizontal intervals, provided that they actually work as hinges (discrete concrete panels).

Transversal flexibility plays an important role during construction, for the correction of the vertical alignment as well as for the development of predictable horizontal stresses. It may have to play a role after construction, in case of significant post-construction settlements or movements of the foundation soil, inducing deformations of the structure.

2.2 *Vertical flexibility*

Vertical flexibility is also obtained from the following

- deformability of the material itself (geosynthetic sheets or grids), or
- shape of the facing units (semi-elliptical steel units), or
- telescopic arrangement of panels (e.g. 'TerraTrel' wire mesh),
- compressibility of the joints or pads placed at regular horizontal intervals (discrete concrete panels),
- placement of each course of units directly on the compacted backfill ("slot storage" panels or from some "green wall" sloping concrete units).

Vertical flexibility is an important concern in regard to construction, in conjunction with the quality and compactability of the backfill, and with the compaction procedure. Lack of vertical flexibility may indeed result, during or after construction, in excessive stresses (hence cracking or spalling), or excessive deformation (bulging) of the facing itself, and/or differential settlement between the facing and the reinforcements, leading to local over-stresses at their connections.

2.3 *Longitudinal flexibility*

Longitudinal flexibility, parallel to the facing, may be obtained from

- variability of the vertical flexibility along the facing, as long as it is available and not absorbed by the compression of the backfill
- inclusion of vertical joints at regular intervals (discrete panels, full height panels). Close vertical joints allow the relatively narrow vertical rows of facing units to move with regard to each other as piano keys. More spaced out joints and wider rows may result in a combination of a piano-keys and a fan-shaped effects, with excessive closure or opening of the vertical joints.
- (contingent) longitudinal sliding of the facing units on top of each other (blocks), or the distortion of the joint filler or pads in the horizontal joints (discrete panels).

Longitudinal flexibility is obviously critical with regard to the anticipated settlements and differential settlements of the foundation soil under the weight of the embankment and reinforced fill structure.

3 PERFORMANCE OF FACING SYSTEMS

A simple measure of movement capacity can be defined for a general panel configuration as shown in Figure 4 where H = panel height, B = panel width, W = panel thickness and joint widths are h (horizontal) and b (vertical).

Flexibility may be represented by

- h/W for transverse flexibility,
- h/H for vertical flexibility, and
- the minimum of h/H or b/B for longitudinal flexibility.

Typical values applied to five types of facing panels/blocks are presented in Table 1. These facing

Table 1. Defonnation characteristics, facing systems

	H (m)	B (m)	W (m)	h (m)	b (m)	h/W	h/H	b/B
Panel, square	1.50	1.50	0.14	0.020	0.015	14.3%	1.3%	1.0%
Panel, rectangular horizontal	1.50	3.00	0.14	0.020	0.015	14.3%	1.3%	0.5%
Panel, rectangular vertical 1	3.00	1.50	0.14	0.020	0.015	14.3%	0.7%	1.0%
Panel, rectangular vertical 2	6.00	1.50	0.20	0.020	0.015	10.0%	0.3%	1.0%
Block	0.20	0.40	0.30	0.001	0.005	0.3%	0.5%	1.3%

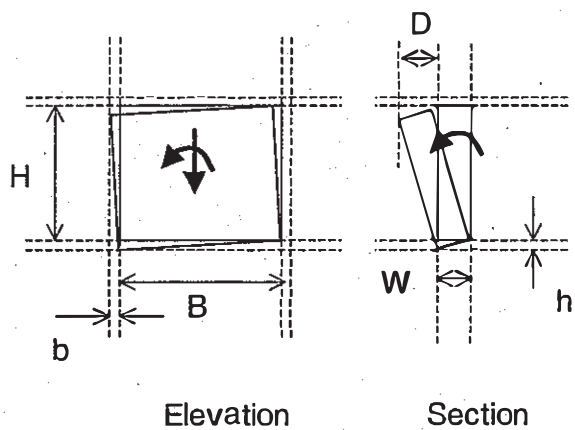

Figure 4. General panel dimensions.

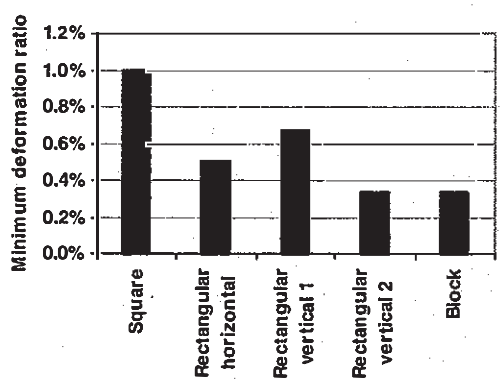

Figure 5. Minimum defonnation ratios.

types, and dimensions assumed are
- square panel, 1.5m (wide) x 1.5m (high) x 140mm (thick), typically the 'TerraClass' system (TAI)
- rectangular panel, horizontally oriented, 3.0m (wide) x 1.5m (high) x 140mm (thick)
- rectangular panel, vertically oriented, 1.5m (wide) x 3.0m (high) x 140mm (thick)
- rectangular panel, vertically oriented, 1.5m (wide) x 6.0m (high) x 140mm (thick)
- segmental block, dry stacked, 400mm (wide) x 200mm (high) x 300mm (thick)

Joint width are taken as
- horizontal joints, 20mm (panels) and 1mm (block) vertical joints, 15mm (panels) and 5mm (block).

From a transverse flexibility perspective, the panel rotational capacity expressed as the ratio, h/W, is less than 0.5% for the block, but greater than 10% for the panels. This effects the ability of the facing system to accommodate lateral movement as the earth structure is constructed and for the reinforcement to mobilise its resistance.

For transverse, vertical and longitudinal flexibility, the joint deformation ratios, expressed as h/W, h/H, or b/B, vary from 0.3% to 14.3%. Only the square panel system achieves a minimum value at, or greater than 1% in all three conditions (Fig.5). With over 10 million square metres in place over 30 years, the 'TerraClass' facing panel system may be considered the benchmark for comparing the flexibility of panel wall systems.

For longitudinal (differential settlement) capacity, the above comparison does not take into account the interaction between rows, or columns, of panels. The panel layout, in elevation, is critical to overall vertical and longitudinal flexibility. Ideally continuous vertical or horizontal joints are required, however, in practice, only continuous vertical joints can provide relatively free movement as horizontal joints are restrained by friction. Vertical oriented panel/block 'stack' configurations are preferred to horizontally oriented panel/block 'stretcher bond' configurations for flexibility.

The overall wall deformation is also the result of the movement of many panels and the redistribution of strains between panels may result in apparently higher deformations without distress.

Examples of gross deformation of Reinforced Earth structures using the 'TerraClass' facing system are shown below.

The structure built in Japan (Fig.6), was built over some very soft material under the central section of the wall which was subsequently found to have SPT values between 0 and 3. The central section settled 1.1m over a length of 58m (between vertical separation joints in the wall). The differential

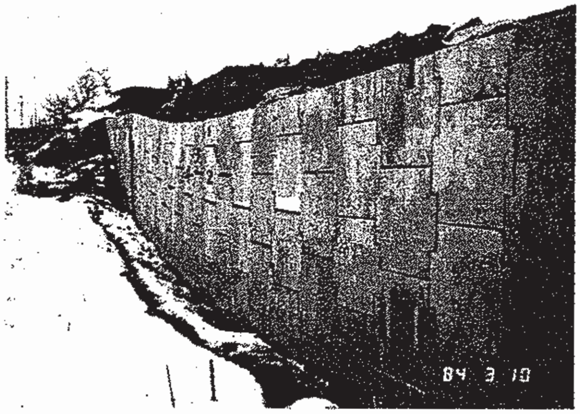

Figure 6. Wall deformation, Japan.

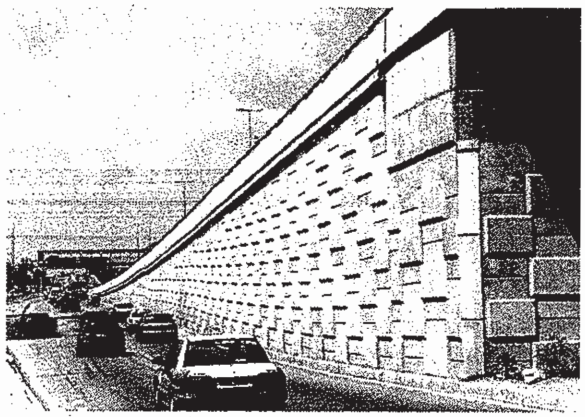

Figure 7. Wall deformation, Malaysia

settlement ($\Delta S/\Delta L$) was over 3.5%, without any significant facial distress or any loss of stability.

The structure built in Malaysia (Fig.7), forms part of a major interchange, and settled significantly due to some soft foundations. The differential settlement ($\Delta S/\Delta L$) observed here is more than 2%, but without distress.

4 PERFORMANCE OF EARTH STRUCTURES

Experience has shown that between 1% and 2% allowance for short term lateral movement due to earth placement and compaction is required. Leaning panels back towards the fill typically accommodates this.

Reinforcement extensibility also has an impact on potential lateral movement. For typical structure-configurations, long term lateral movement of between 0.5% (for inextensible reinforcement) and 1.5% (for extensible reinforcement) is possible (Mitchell & Christopher,1990). Such deformation potential is related to structure configuration as shown in Figure 8 (where L is the length of the reinforcement).

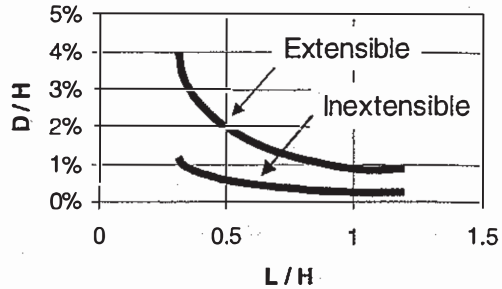

Figure 8. Post-construction lateral deformation.

5 STRATEGIES FOR IMPROVING FLEXIBILITY

Improvement in flexibility may be achieved by
- articulation of hard panels and blocks through flexible joint design,
- promotion of bending with thin sheets or mesh, or
- provision for sliding of panel/reinforcement connections in continuous, or rigidly connected facing units

Flexible joint design in panel systems is usually achieved with cork strips or rubber pads in the horizontal joints. The use of cork has been generally superseded in order to obtain better durability and performance characteristics. Rubber pads with a two phase load/deflection relationship (Fig.9) allows for improved initial flexibility (during construction) while providing longer term stiffness to avoid concrete to concrete contact under possible severe long term imposed deformations.

For block systems, an improvement in vertical flexibility may be achieved by inserting geotextile in the horizontal joints between each block. For a 200mm high block, a residual joint width of 2mm is needed to provide a vertical compression ratio of 1%.

For thin flexible sheet, or mesh, facing systems, their vertical flexibility may be promoted by optimising their (section) shape to follow the vertical and horizontal deformations of the earth fill behind. Vidal (1966) recognised this when he introduced Reinforced Earth and proposed that the semi-elliptical shape of metallic facing panels be proportioned according to the expected ratio of lateral and vertical movement in the earth mass.

A simple three-hinge panel model in Figure 10 illustrates the lateral (buckling) deflection behaviour for a plane sheet, under in-plane compression. The initial lateral deflection is shown to be very much greater than the axial deformation. The consequences of this are that
- the lateral deflection can rapidly exceed normal wall deformation tolerances, and
- the panel may laterally move away from the fill.

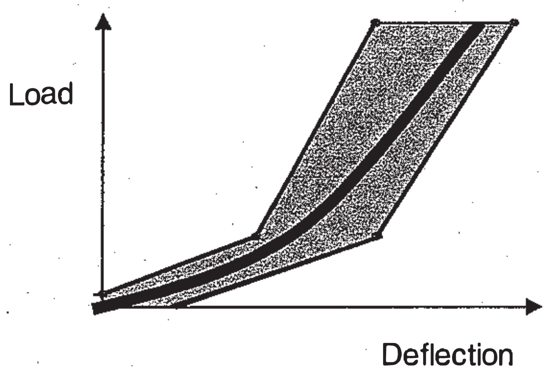

Figure 9. Load/deflection relationship for rubber bearing pads.

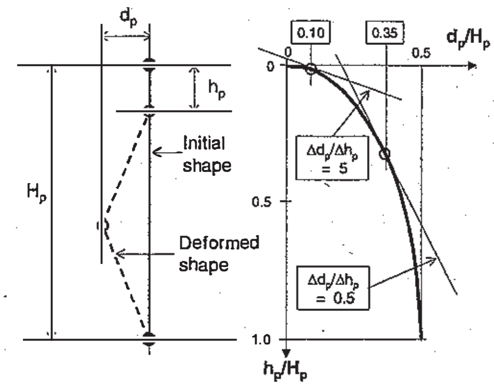

Figure 10. Vertical/horizontal defonnation compatibility.

For an initial panel height of H_p, small initial vertical deformation (h_p) will result in large lateral deflection (d_p). For example, only 2% vertical compression (h_p/H_p) results in 10% lateral deflection (d_p/H_p), which is equivalent to 100mm lateral deflection over a 1m panel under 20mm compression. Also, high initial rate of change of lateral deformation to axial deflection ($\Delta d_p/\Delta h_p$), does not reduce to a value appropriate to a granular fill (typically 0.5) until the ratio of lateral deflection to initial panel height (d_p/H_p) is approximately 0.35.

This suggests that without other means of vertical flexibility (telescoping panel sheets, or sliding connections), the initial sectional proportions of such a panel must be sufficient to avoid panel separation from the backfill and creation of voids.

6 CONCLUSIONS AND RECOMMENDATIONS

Flexibility has been defined in terms of the ability to deform transversally, vertically and longitudinally. A preliminary quantitative assessment of the flexibility characteristics of flexible facing systems has been presented which highlights the relative ability of systems to deform. Strategies for improving flexibility have been outlined.

Further studies are proposed in order to better under stand the interaction of panel and block systemsunder different movement influences, together with the impact on mobilisation of forces in the structure and reinforcement and overall structure behaviour.

On the basis of the experience to date, the characteristics of the most common types of facings based on their larger or smaller ability to deform in the three directions are qualitatively described in Table 2. Four degrees of flexibility are considered: good, medium, limited, non existent. This provides a basis for comparison and evaluation of structural impact.

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Table 2. Qualitative flexibility characteristics of common facing systems.

Type of facing	*Comments*	Transversal flexibility	Vertical Flexibility	Longitudinal flexibility
Square discrete panels	*With compressible horizontal joints or pads*	Good	Medium	Good
Wide discrete panels	*With compressible horizontal joints or pads*	Good	Medium	Medium
Narrow full height panels	*Without sliding, or movable connections.*	Limited	Non existent	Medium
Wide full height panels	*Without sliding, or movable connections*	Limited	Non existent	Limited
Wire mesh facing		Good	Good	Good
Wire mesh facing + CIP concrete	*Once covered with cast in place concrete*	Limited	Non existent	Non existent
Semi-elliptical steel face		Good	Good	Good
Blocks	*Without joint material*	Limited	Non existent	Limited
Wrapped around		Good	Good	Good
Wrapped around + shotcrete	*Once covered with shotcrete*	Limited	Non-existent	Non-existent