SRW HISTORY ARTICLE SERIES

SRW RESEARCH

This is the fourth article in a series of ten articles on the history of segmental retaining walls developed under a grant from the NCMA Education and Research Foundation.

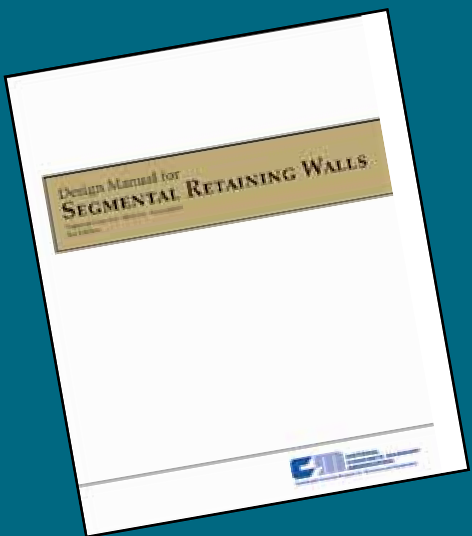

Figure 1. Design Manual for Segmental Retaining Walls, 3rd Edition

SEGMENTAL RETAINING WALL RESEARCH

The concept used for gravity walls and Mechanically Stabilized Earth walls (MSE) is not new; there are structures over 4,000 years old that were built with similar principles. Segmental Retaining Wall (SRW) systems are applying the same concept with a fairly new technology, manufactured concrete units and geosynthetic soil reinforcement. Since its introduction in the 1980's, advancements have been made by the continuous research and development.

The National Concrete Masonry Association (NCMA) and its membership have been leaders in developing, researching, and promoting Segmental Retaining Walls (SRWs). SRWs started in North America and are now manufactured and installed in countries all around the world. The design methodology followed in most worldwide locations is the NCMA SRW Design Manual, one of the first research tasks taken on by NCMA to help develop this new market. Other research projects have included: Test methods, freeze-thaw durability, single depth, multi-depth, mechanically stabilized earth walls (MSE), and seismic performance.

DESIGN MANUAL

Geosynthetic soil reinforcements were introduced into the market in the 1970s. Steel reinforced wall technology was already established in the US in the early 1970s. In the 1980s, an innovator in the US developed a concrete retaining wall system that used zero-slump concrete products as the facing units and geosynthetic reinforcements as the soil reinforcing system. This system became a popular construction item but left designers with questions that had not yet been answered: design methodology, durability of construction elements, testing methods for product characteristics, and quality assurance. The NCMA SRW Design Manual was developed to help answer these questions (see Fig. 1).

Design

In the previous article of this series on SRW Design (Ref. 15), we referenced the initial work by Professor Bell (Bell 1975, Ref. 4) designing geosynthetic reinforced slopes for landslide correction on the Oregon Coast. In designing with geosynthetics, Professor Bell used the active Rankine lateral earth pressures. In manuals published later by geogrid manufacturers (Simac 1990 and Tensar 1990, Ref. 22 and 29), and design methodologies published by the FHWA (Task Force 27 1990, Ref. 28), the earth pressures were calculated using the Rankine methodology as well. In the transportation market, the design methodology used was the gravity earth method based on the use of steel (non-extensible) reinforcement. These two design methodologies were significantly different and the industry needed a consistent design methodology with industry accepted factors of safety for the proposed materials used in construction: zero-slump concrete facing units with geogrid (extensible) reinforcement. NCMA contracted with industry experts to research and prepare an industry accepted design manual.

NCMA Design Manual, Versions 1993, 1997, 2009

The first NCMA Design Manual for Segmental Retaining Walls was published in 1993. The methodology used was an active Coulomb earth pressure using friction between the concrete facing and the reinforced fill soil. This was a less conservative methodology than used by Professor Bell (Ref. 4), geogrid manufacturers, FHWA, and a different methodology than the gravity earth method used in the transportation markets. The Coulomb design approach accounted for batter of the wall and resulted in a more aggressive design. The approach was new at the time to MSE design, but was based on appropriate design approach that was concurrent with extensible soil reinforcing elements, and geogrid reinforcing. Research (Allen 2001, Ref. 2 and

Geocomp 2009, Ref. 10), has shown that the calculated loads were double the measured loads from constructed walls, a progressive move by NCMA and the SRW industry.

The design manual was revised in 1997 (Ref. 6) with updates and additions to the design manual and again revised in 2009 (Ref. 8), adding the Seismic Design Manual (Ref. 20) and the Drainage Design Manual (Ref. 8) to the main Design Manual.

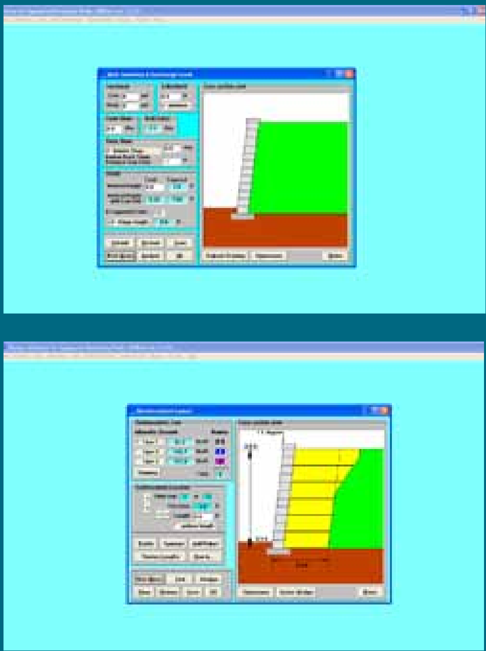

Figure 2. SRWall 3.22 Screen Shots (2002)

Seismic Design Manual

Due to interests in seismic design methodologies, NCMA contracted with industry experts to write a seismic design manual to complement the Design Manual for Segmental Retaining Walls. This manual was published in 1998 and is based on the Mononobe Okabe method of analysis for pseudo static design (Whitman 1990). The methodology was revised in the third edition of the Design Manual for Segmental Retaining Wall (Ref. 8) in 2009 to incorporate Ling H. et al. research (Ref. 12) and proven field performance. This research changed the seismic force used from an inverted trapezoid (maximum dynamic force near the top of the structure) to a rectangular load distribution. For more details on the design implications refer to the SRW Design article (Ref. 15).

Test Methods

The NCMA design manual references connection strength between the SRW units and the geogrid reinforcing and shear strength between units for design. No test methods were available at the time of the first writing so two methods were created to provide a methodology to test the SRW-geogrid systems: Connection Strength - SRWU-1 and Shear Strength – SRWU-2. Both of these test methods have been adopted by ASTM as standard test protocols: Connection Strength: ASTM D6638 and Shear Strength: ASTM D6916 (Ref. 25 and 26). ASTM D6638 evaluates the peak connection strength of the unit-geogrid connection, and does not consider sustained load (creep) connection capacity as suggested under AASHTO/FHWA (Ref. 1). ASTM D6638 has served as the basis for NCMA design since 1993 (20 years) and has been associated with the successfully performance of millions of square feet of retaining wall around the world, including structures in high seismic regions as documented after the earthquakes in Northridge, CA, and Chile.

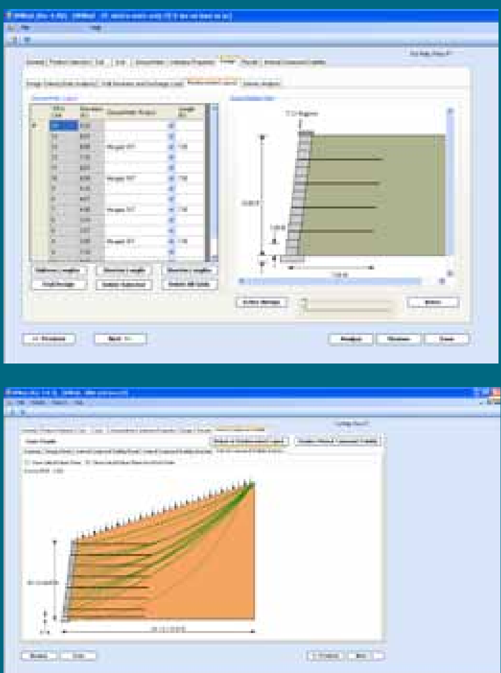

Figure 3. SRWall 4.0 Screen Shots (2009)

DESIGN SOFTWARE

The Design Manual was a great asset to designers and specifiers of SRW walls. Several of the geogrid manufacturers provided software for designing walls with their materials; however there was not an industry-provided software for designers that would design all systems with a consistent methodology. In 1992, NCMA contracted with the authors of the Design Manual to write the SRWall design program that was consistent with the provisions contained in the design manual. The first version of the software was released in 1993 and multiple versions have come after to accompany the different editions of the design manual. A fourth version of SRWall was released in 2009 that included the changes made in the third edition of the manual (See Fig. 2 and 3).

PERFORMANCE IN SEISMIC CONDITIONS

Observations

Several significant seismic events occurred around the world between 1994 and 2010 where the performance of segmental retaining walls was reviewed and multiple papers documented their performance (Sandri 1997, Race 2001, Yen 2011, NISEE 2006 Ref. 18, 17, 31 and 14). In each event SRW walls experienced little to no wall movement or damage. As stated for the Chilean earthquake (Yen 2011, page 142, Ref. 31): "In general, all of the observed walls performed well." The Chilean earthquake was measured at 8.8 on the Richter Scale and lasted for more than two minutes.

The January 17, 1994 the M6.7 Northridge earthquake in the Greater Los Angeles area was the first event where the behavior of tall SRWs was documented. Sandri, 1994 (Ref. 18) reported that none of the Southern nine SRW walls (all taller than 15 ft (4.6 m)) observed after the earthquake had shown any evidence of distress (40 to 70 miles (64 to 113 km) away from the epicenter). In walls near the epicenter of the earthquake (14 and 22 miles (23 to 35 km) away), the walls exhibited tension cracks in the soil between the reinforced zone and the unreinforced soil. This movement had no detrimental effect on the walls performance. In a summary statement by Sandri "The observations presented … suggest that geosynthetically reinforced soil structures provide an excellent choice for grade change transitions."

AASHTO

Based on results from the above research and years of observing walls after earthquake events lead to a revision of Version 6 of the AASHTO Bridge Design Manual (AASHTO 2012, Ref. 1).

Article 11.5.4.2 states:

> *"A seismic design shall not be considered mandatory for walls located in Seismic Zones 1 through 3, or for walls at sites where the site adjusted peak ground acceleration, As, is less than or equal to 0.4g, unless liquefaction induces lateral spreading or slope failure, or seismically induced slope failure, due to the presence of sensitive clays that lose strength during seismic shaking, or if the wall supports another structure that is required by code or specification to be designed for seismic loading."*

Article C11.5.4.2 states:

> *"In general, wall performance in past earthquakes, and cases where either wall collapse or severe wall displacements have occurred are rare." Further it states: "walls meeting the requirements in Article 11.5.4.2 that allow a seismic analysis to not be conducted have demonstrated consistently good performance in past earthquakes."*

FREEZE-THAW

Freeze-thaw durability of concrete products has always been a concern for both wet-cast and zero-slump concrete products. The use of chemicals to help deice highways and sidewalks has increased the degradation of concrete under repeated freezing and thawing conditions. This concern was brought to the SRW industry in the early 90s as cities in the upper mid-west were seeing degradation of concrete SRW walls.

Research

The Minnesota Department of Transportation and NCMA initiated a study on the extent of freeze-thaw degradation in the greater Minneapolis area (Embacher 2001, Ref. 9). To further determine the effects of freeze-thaw degradation to zero-slump products, the Federal Highway Administration (Chan 2007, Ref. 5) contracted with industry experts to research freeze-thaw on SRW products.

Figure 4. Transportation Project Application (Courtesy of Allan Block)

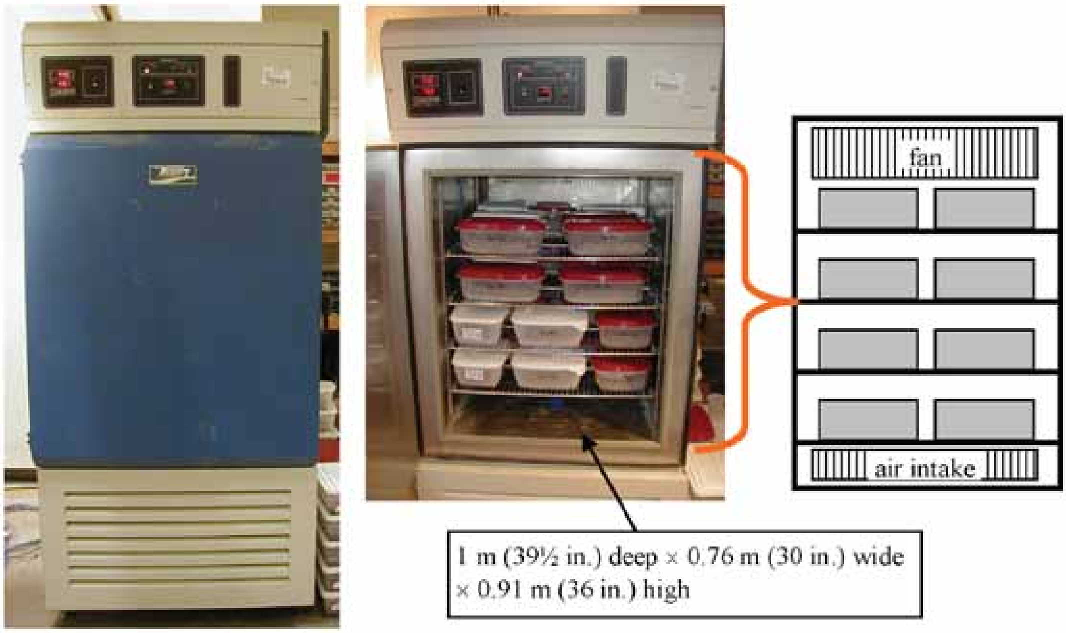

Figure 5. Freeze-Thaw Testing Chamber

NCMA has conducted a significant amount of in-house research on freeze-thaw degradation and contracted with industry experts to investigate SRW durability. That research is listed in the NCMA paper on Freeze-Thaw Durability (NCMA 2012 , Ref. 16). Much of the information is unpublished, but a wealth of information is available upon request.

One effort NCMA attempted was to establish a "Frost Durability Index" for durability based on absorption, density and concrete content (SEM 2004, Ref. 20). While the concept was good, research has found that none of the indices used provided the key to successful performance. The key to improved performance is low permeability (low absorption and high compaction effort), increased water for better hydration (better chemical additives), higher tensile capacity (higher cement content), and durable aggregates. Results show that testing per ASTM C1262 was the best indicator of a good performance (Fig. 5).

Test Methods

When freeze-thaw durability concerns were noted, there were no test methods available for freeze-thaw testing on zero-slump concrete products. The Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (ASTM C666) was the standard test method for wet-cast concrete, but the sample size and submerged test method was not applicable to SRW units. NCMA developed a freeze-thaw test method applicable to zero-slump concrete, Standard Test Method for Evaluating the Freeze-Thaw Durability of Dry-Cast Segmental Retaining Wall Units and Related Concrete Units (ASTM C1262) that is used if freeze thaw is a concern following the recommendations of ASTM C1372, Standard Specification for Dry-Cast Segmental Retaining Wall Units (Ref. 24).

Continued Research

ASTM C1262 is the accepted standard for the industry, but NCMA is continuing to research the test method to obtain more consistent and repeatable results. The current test method exhibits varying results depending on the freeze-thaw cycle time and rate of freezing and thawing. Fig. 5 shows the testing equipment used. For more information on this topic refer to the article The Durability of Segmental Retaining Walls (SRW) Units (Ref. 16).

UNIT DESIGN

Configuration

The configuration design of SRW units began with modifications to the standard 8 x 8 x 16 in. (203 x 203 x 406 mm) masonry unit (CMU) as this was the standard size manufacturing equipment could produce. The height of the units varied from three in. up to eight in. (76-203 mm), with some equipment cable of making a one foot tall (0.3 m) unit. The need for a shear connection between units lead to different configurations such as units with pin connections, concrete lips on the front or back of units, or concrete nubs or lugs. The minimum face shell thickness of 1.25 in. (32 mm) for a CMU was increased all the way to full solid units, as well as units using internal cores and different layout geometry. There has been no formal research into the unit designs other than what has been easy to produce consistently and a unit size that is preferred by the customer. The market tends to dictate what is acceptable.

Face Panel

The area that has received a lot of research is the face panel. The early units were a form finished design, either straight or fluted. Later a roughened surface was provided by splitting off two to three in. (51 to 76 mm) of hardened concrete to form a split faced unit. These designs were either straight or in a three plane split. As the industry grew, inventors tried putting a roughed plate in the mold for a Soft Split™ design or an Abraded™ face. Some examples are shown in Fig. 6 and 7.

Over the past 10 years manufacturers have gone to a pressed face where the face of the mold has an imprinted pattern pressed on the unit during manufacturing, the face is pulled back during extraction and the resulting product has a formed face. Again there is no formal research on these developments, the development information is proprietary to the company and the market decides if the product is acceptable.

Unit Design

Above we spoke about the units being modeled after a standard CMU unit and manufactured in a standard 18 x 24 x 8 in. (457 x 610 x 203 mm) mold box. These are typical for single depth SRW walls. In the previous paper on SRW Design we talked about multi-depth units. In multi-depth walls there are several components that hook together to form deeper units that function well as taller gravity walls. Multi-depth units were marketed in the early 1990's and now are available for sites where access is limited for MSE walls.

PERFORMANCE OF SEGMENTAL RETAINING WALLS

There have been many papers published on the performance of SRW walls but recent research papers demonstrate the conservative nature of SRW design. NCMA funded a recent research project parallel to an NCHRP study on the use of non-select backfill with MSE wall design (Geocomp 2009, Ref. 10). The results showed that soils with as much as 25% fines and a Plasticity Index below 6% could be successfully used as backfill materials in MSE structures, provided the design used the appropriate material properties and took into consideration any positive water pressures that may develop in the backfill over the life of the structure.

All the measured loads on the NCMA 20 ft (6.1 m) test walls were less than the predicted values for the 5 ft (1.5 m) of soil surcharge, and full hydrostatic pressures

Figure 6. Hard-Split SRW Facing (Courtesy of VERSA-LOK)

Figure 7. Soft-Slip SRW Facing, Tumbled (Courtesy of Keystone)

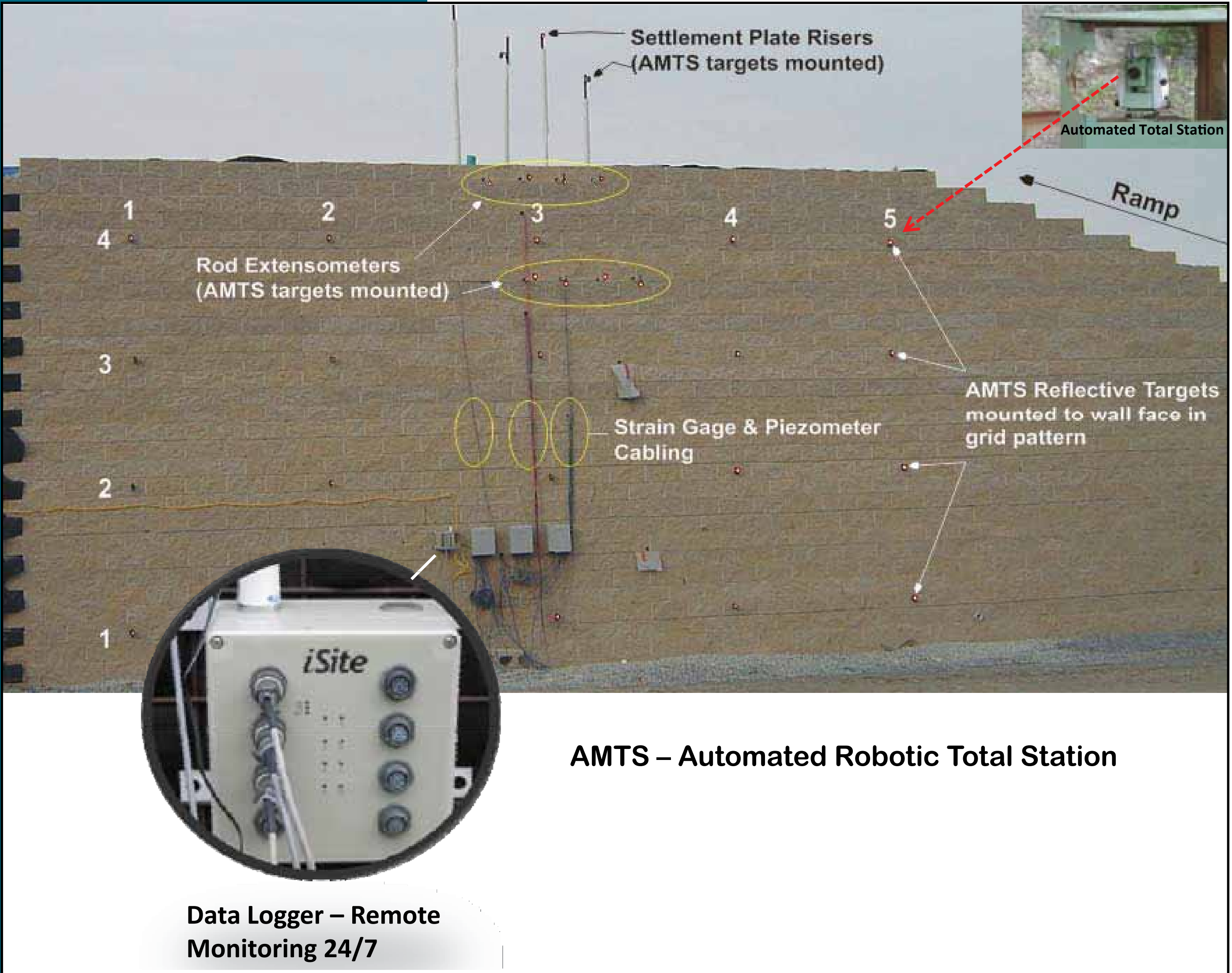

Figure 8. Full Scale SRW Research (Ref. 10)

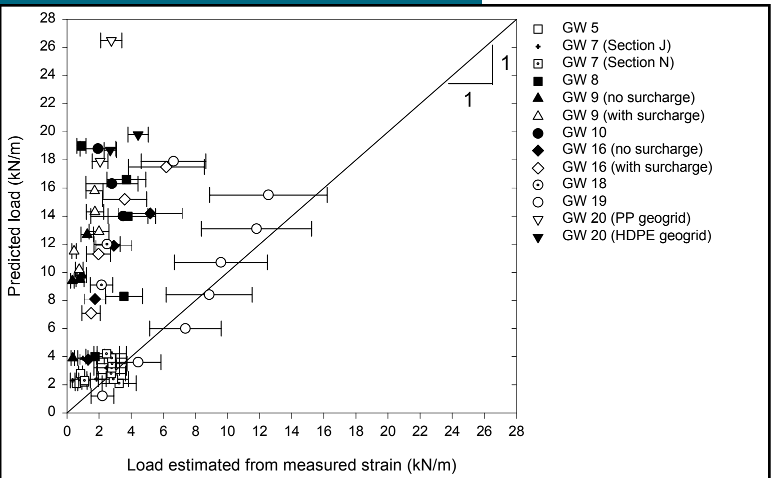

Figure 9. Predicted Versus Reinforcement Load Estimated From Strain Measurements For Full Scale Field Geosynthetic Walls, Using The AASHTO Tie-Back Wedge/Simplified Method. (Ref. 2, Fig. 5.1)

conditions generated. (See instrumentation on Fig. 8). These findings will eventually give designers more flexibility when selecting backfill materials and could potentially change the design methodologies.

NEW DEVELOPMENTS AND INDUSTRY TRENDS

K-Stiffness Design

For several years Mr. Tony Allen (Washington Department of Transportation) and Dr. Richard Bathurst (Royal Military College, Kingston, ON) researched instrumented walls, conducted extensive laboratory testing, and confirmed the data with numerical studies and have shown the current AASHTO Simplified method (and NCMA method) over-predicts loading in the reinforcement (Allen 2003, Ref. 2). As noted in Fig. 9, the predicted load is much greater than the loads recorded in instrumented geogrid wall structures.

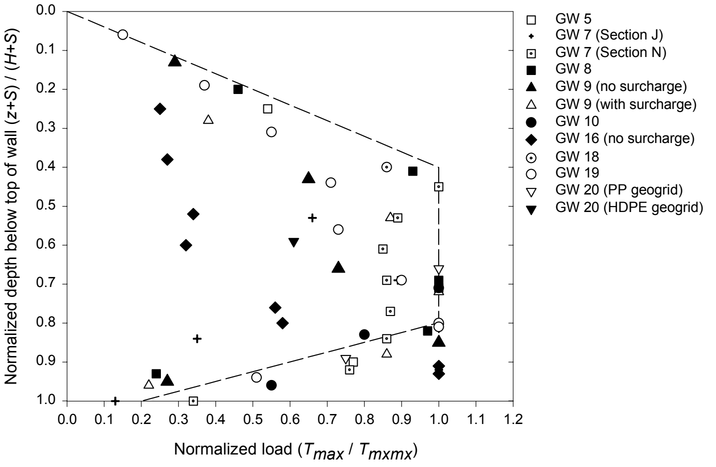

Figure 10. Normalized Load Estimated From Strain Measurements As A Function Of Normalized Depth Below Wall Top. (Ref. 2, Fig. 5.4)

Another interesting result of the research was the fact that the loads did not increase all the way to the base of the structure (P = γKa Z where γ is the unit weight of the soil, Ka is the active lateral earth pressure coefficient, and Z is the depth of soil to the analyzed point.); the loading was more of a trapezoidal shape (Fig. 10).

Research by Holtz and Lee (Ref. 11) plotted predicted versus measured stresses from an SRW/geogrid retaining wall. The results also confirmed the data Allen and Bathurst were presenting. Based on the strains (tension) in the reinforcement, the AASHTO Simplified approach would have predicted loading of 2,100 lb/ft (31 kN/m) whereas the measured values were only 400 lb/ft (6 kN/m) (see Fig. 11).

In a series of research papers by Allen and Bathurst it was shown the stiff faced SRW walls were over designed for internal analysis by a factor of greater than two (Bathurst 2006, Ref. 3) resulting in final factors of safety greater than 3.0 or 4.0 (See Fig. 12). The influence of a stiff face was also shown in the results from the Geocomp research.

In a paper by Professor Holtz (Ref. 11) he discussed the history and development of geogrid reinforced soil structures (GRS). In his concluding remarks he predicts: 1) GRS will soon be the "standard steep slope" and "standard wall" because of their significant advantages; and 2) GRS and other types of reinforced walls will change the way we teach earth pressure theory and the design of backfilled retaining structures."

FHWA's Turner-Fairbank Highway Research Center continues to study GRS structures and the composite behavior of closely spaced reinforcement (8-12 in. (203-305 mm)). The composite behavior is showing little internal stresses and the method currently does not consider geosynthetic-block facing connection. This new technology is being used in pilot projects around the U.S. but it is not yet included in any code.

NATIONAL AND INTERNATIONAL INTEREST

NCMA and its membership have provided a good base of leadership and research into developing GRS systems using zero-slump concrete products (SRWs). A small amount of the key research is referenced in this paper, but the referenced documents will lead the reader to much more detail.

The American Association of State and Highway Transportation Officials (AASHTO) has reviewed the seismic research and it helped adopt changes to the current design code. ASTM has adopted several of the proposed NCMA test standards (ASTM

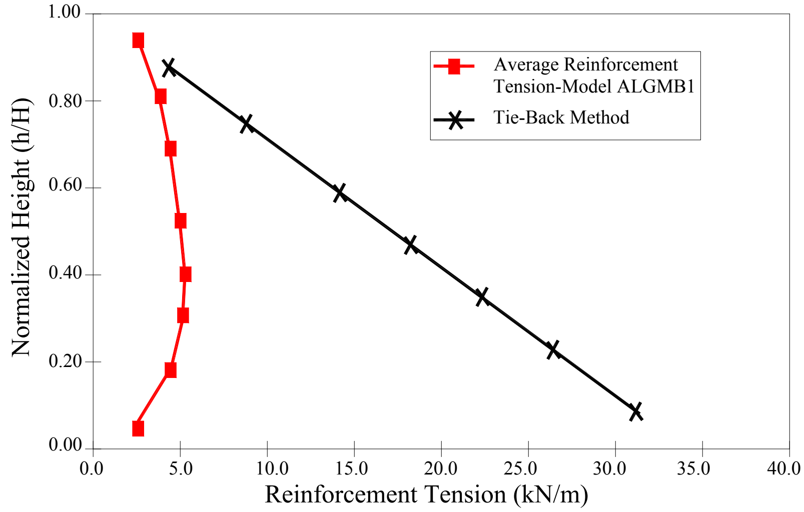

Figure 11. Distribution of Reinforcement Tensions of Algonquin Modular Faced Wall (Ref. 11, Figure 9.5.4)

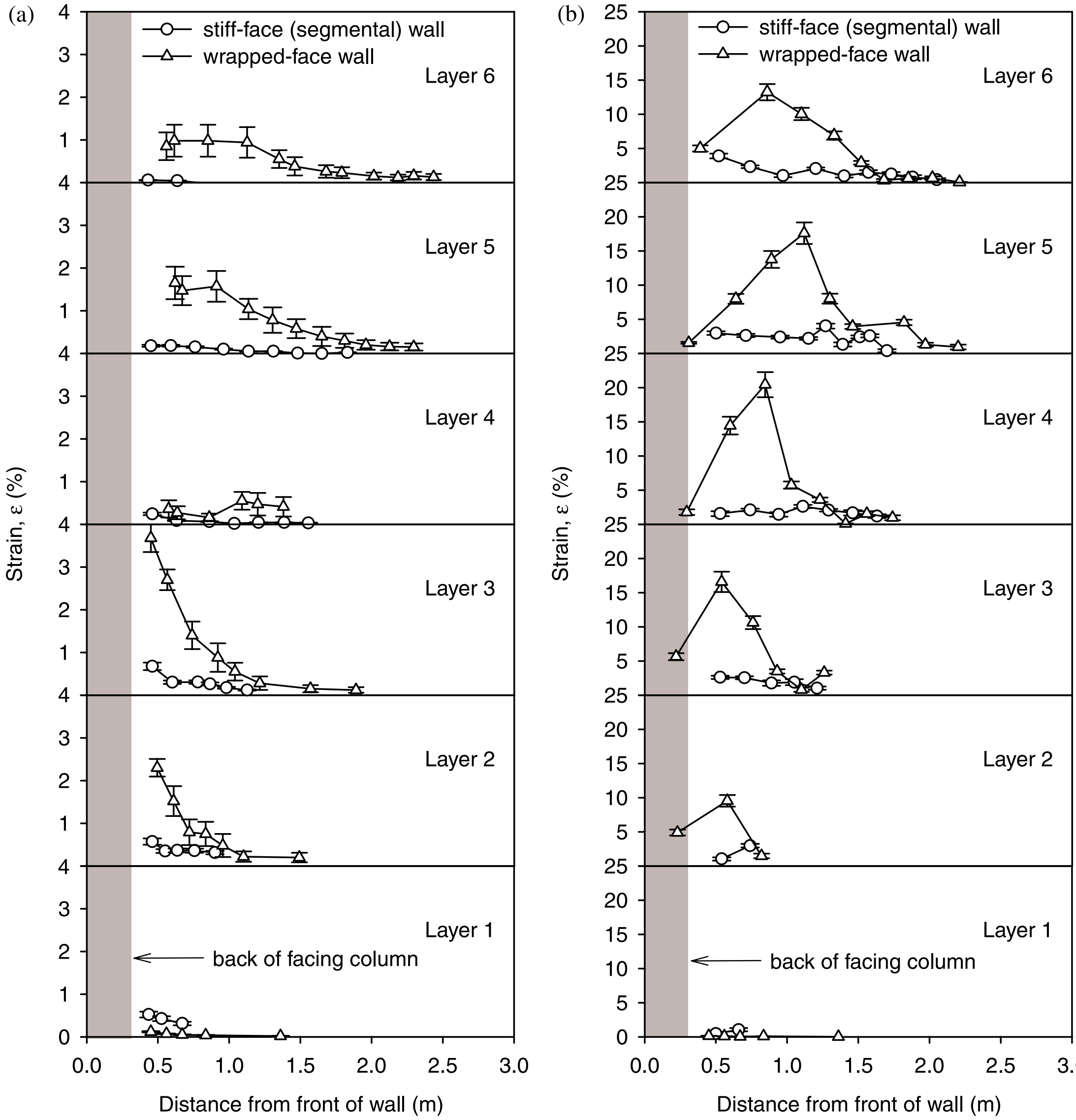

Figure 12. Reinforcement Strains At: a) End of Construction, b) 80 kPa Surcharge (Ref. 3, Figure 9)

C1262, ASTM C1372, ASTM D6638 and ASTM D6916) that were developed for SRW unit and assembly testing and specifications. The local research has helped develop SRW systems which are manufactured and sold all over the world. There is no doubt that SRWs are one of the largest types of retaining wall systems manufactured and sold worldwide. The technology is relatively new so it is expected to see more improvements to products and design methodology in the future.

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