FRICTION AND TENSILE STRENGTH OF EARTHBAG COMPONENTS

Preliminary test report, September 25, 2010

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Above: The top earthbag is held up by barbed wire alone

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ABSTRACT

How much strength does the matrix of barbed wire and poly bag surfaces between courses contribute to earthbag building walls?

The use of well-known formulas based on concrete masonry building codes for earthbag design limits it to infill material supported by structural skin or post and beam systems. According to the new international earthen building standards, if earthbag walls with some reinforcing have shear strength equal to or greater than reinforced adobe they can be designed for building structure even in the most risky seismic regions.

Since shear strength is related to friction between courses, soil filled poly bags were tested by a simple tilt table method to discover the approximate coefficient of static friction between the bags with barbed wire. Additional tests used barbed wire and metal pins, or pins alone. The force needed to pull barbed wire out axially from between bags was also tested.

Results from more than 20 tilt tests indicated that full, moderately firm bags have coefficients of static friction between 1.5 and 1.9, up to 3 times higher than those needed to create an unreinforced geo-cell wall. Higher coefficients of friction (up to 2.7) resulted from providing small metal pins with 2 points. Length of barb did not appear to affect the coefficient of friction.

Results from two axial tension tests indicated that barbed wire does not pull out until the barbs bend. Although static friction was overcome at 60- 80 pounds force, 120 pounds was required to remove the wire completely from between two partially cured bags.

INTRODUCTION

Earthbag is an innovative building technology being built increasingly around the world. At present buildings are known to exist in 25 countries and in 15 US states.

Because of its simplicity and low cost, earthbag is spreading into high seismic risk zones. At least seven buildings have been built in the last year in Haiti, and many more are in the planning stages. How much reinforcement is needed for earthbag in medium and high seismic risk regions?

Plastered earthbag resembles a wide concrete block wall. Wall layouts are often similar to adobe buildings with bracing from intersecting walls or piers. Traditional roofs, windows, and doors are used with earthbag walls.

Above: A small classroom building under construction near Leogane, Haiti

Earthbag construction uses moist subsoil containing 5- 50% clay (or more clay) in poly bags. These are tamped and laid in an overlapping running bond pattern like bricks. Barbed wire is used both as a mortar and as tensile reinforcement between each layer of bags. The bag walls are strongest if covered promptly with earth or cement plaster to prevent degradation of poly material by sunlight. Standard footings and bond beam can be used with inserted rebar and innovative systems of strapping, metal wall stiffening, and mesh-reinforced plaster in earthbag buildings.

BUILDING STANDARDS AND EARTHBAG

Earthen buildings of various kinds are increasingly recognized as the future of sustainable building. Popular earthbags when built of 'raw' earth without cement, lime, or gypsum stabilizers use 1/6 or less of the embodied energy of comparable brick construction.[1]

Only scattered regions have earthen building standards, and many of these concentrate on adobe or stabilized earth techniques. Most of North and South America, Africa and Europe lack any earth building code, and all lacks one that can be applied to earthbag.

Few engineers work on structural designs for earthbag. In the US rectangular earthbag buildings have been built as infill confined like unit masonry within a separate post and beam system. Some engineers are beginning to design earthbag structures like concrete masonry, relying on cement structural skins and reinforcing steel in amounts comparable to that required for concrete block or brick.[2] Any engineering is reassuring for larger buildings in high risk regions. Better structural design formulas require more testing.

Raw earthbag walls are much more flexible than concrete walls. In an earthquake minor slipping between adjacent surfaces within walls can absorb large amounts of energy. Flexible wall systems can better survive horizontal loading without permanent damage.

Existing unreinforced adobe buildings with added mesh and plaster containment may need plaster repaired but avoid major structural damage.[3] Structural straw-bale buildings on gravel bag footings flex to survive shake table tests with much less reinforcement than masonry, coated only in earth plaster.[4] Civil engineers prefer proven geo-textiles for large retaining walls instead of stiffer structures. Unreinforced geo-cell layers are filled with tamped soil and stacked in layers.

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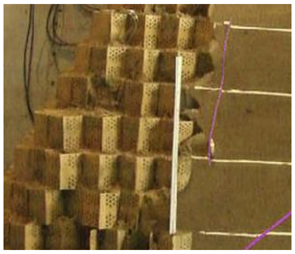
[1] Earthbag of new bags with barbed wire = 131,500 btu/ linear foot (MJ/m); Brick = 720,000 btu/ linear foot (2480 MJ/m)

[2] Nabil Taha, *Is Earthbag Construction Like Masonry Construction?* Precision Structural Engineering Services http://www.structure1.com/earthbag6.htm accessed September 25, 2010

[3] Daniel Torrealva, Newman, J.; Blondet, M.; *Earthquake Resistant Design Criteria and Testing of Adobe Buildings,* (Peru: Pontificia Universidad, undated) accessed at https:// getty.edu/conservation/publications.pdf 8- 23-2010

[4] Darcey Donovon and Earthquake Engineering Research Institute, *Seismic Performance of Innovative Straw Bale Wall Systems,* (Truckee, CA, PAKSBAB Pakistan Strawbale and Appropriate Building, March 2009) accessed at http://nees.unr.edu/projects/straw_bale_house.html 8- 23- 2010

Structural design of geo-cell walls must support weight of soil adjacent as well as soil in the cells. It is strong enough if the coefficient of friction between the unconnected grid and soil surfaces is equal to half of the expected peak ground acceleration. [5] One seismic design expert expects similar friction levels, more than added reinforcement, to be vital to the stability of earthbag buildings. [6]



Right: Geo-cells after severe shake test

2010 International Earth Building Standard

In May of this year ASTM International published revisions to *E2392 Standard Guide for Design of Earthen Wall Building Systems*[7] that apply specifically to un-engineered 'raw' earth buildings to provide guidance for engineers and building officials.

The 10 page document states that existing standards for concrete and concrete masonry construction are more applicable to cement-stabilized earthen structures than to raw earth buildings. Appendix X1 of *E2392* was developed primarily to assist with raw earth buildings, which do not need a cement stucco structural skin (and should not receive cement stucco). The appendix applies to single story buildings in regions with more than 10% risk of exceeding Mercalli intensity IV, and to higher buildings in medium seismic risk areas (Mercalli scale V or VI) or less.

Right: Architect checks an earthbag structure in Kentucky

Appendix X1 lists empirical design and minimum detailing recommendations. Some of these are familiar from historic adobe codes. But it also recommends information in New Zealand's earth standards (NZS 4297, 4298 and 4299)[8]. Thus strategies listed in *E2392* can best be used on the same types of buildings that qualify for *NZS 4299, Earth Buildings not Requiring Specific Design*. Specific engineering should not be needed on simple office, residential, industrial or warehouse structures of:

- 600 m^2 or certain 300 m^2 per level buildings in areas with low or medium risk
- With concrete footings and short wing walls
- Of strong soil mixes on good bearing soil and grading
- In climates without the most extreme wind, snow, or rainfall

Non-engineered Earthbag Design

E2392 includes earthbag in the list of common earthen construction systems. Engineering judgment can be used to apply the included guidelines to earthbag. Experience of earthbag buildings indicates that earthbag probably has similar or greater strength than unreinforced adobe. (Evidence of walls that were undamaged by auto collisions or very difficult to disassemble imply equal or superior strength to adobe). If so, earthbag can easily fulfill ASTM guidelines for low seismic risk areas. If earthbag walls with some reinforcement have similar or greater stability than reinforced adobe, the guidelines can also be applied in medium risk areas.

E2392 recommends selecting the most practical combination of strategies to provide structural continuity, out-of-plane stability, and containment. Strong or flexible bond beams, vertical and/ or horizontal reinforcing, bracing elements, and containment are listed. Stable building geometries are also important. This is obvious from with the proven intrinsic strength of dome or round-wall buildings. (Unfortunately rectangular buildings are often needed to satisfy ventilation requirements and cultural preferences). Symmetrical or regular buildings with less than 1/3 wall openings and 1.2 m between windows or windows and corners are important.

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[5] Dov Leshchinsky, Ling, Wang, Rosen, and Mohri, *Equivalent Seismic Coefficient in Geocell Retention Systems,* (Geotextiles and Geomembrances, Volume 27:1, February 2009) 9- 18

[6] Dov Leshchinsky, personal email dated 8/9/2010 "The factor of safety against the wall sliding (i.e., collapsing) is Fs=Pr/Ph=f/PGA. I would expect this Fs to be larger than 1.5 or even 2 …using PGA could be very conservative as the load is applied for a fraction of a second … I am using PGA/2. …such reduced design acceleration is applicable for your walls as well."

[7] ASTM International, *E2392/E2392M- 10* available for purchase from www.astm.org .

[8] Available for purchase from www.standards.co.nz/.

If earthbag walls are as strong and stable as reinforced adobe (either with or without added rebar and/ or horizontal stiffeners) a few simple measures can prepare them for high seismic risk zones. These would include full wall containment with either height-to-thickness limits or base protection and stronger top-of-wall attachment.

Engineered Earthbag Design

Using information from *E2392* and *NZS 4299* together, earthbag buildings that should be engineered would include structures:

Larger or taller
With rubble or gravel bag footings
For uses essential for emergencies or hazardous
For high occupancies like assembly halls and large schools

If concrete masonry guidelines do not apply to raw earth buildings, how can earthbag structures be appropriately engineered? E2392 states that traditional stress analysis design is 'much less reliable' than analysis of global and local stability. Engineers should use strength (load and factor) design to estimate seismic design loads on elements.

The New Zealand standards do this, based on data from building shake table tests and diagonal compressions tests of wall portions. But they are calibrated to the performance of unreinforced and reinforced earth block and reinforced rammed earth.

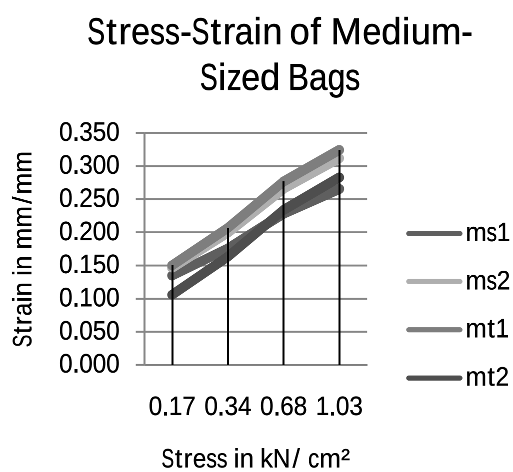
Right: Hammering vertical rebar into earthbags

Tests of entire rectangular earthbag buildings are needed to fully understand earthbag walls' structural performance. But tests of earthbag components and wall portions can begin to indicate how closely earthbag shear strength approximates adobe with or without reinforcing. If earthbag walls can be compared to other earthen materials, non-engineered rectangular buildings can benefit from the charts for bracing walls included in the New Zealand guidelines. These charts specify lengths and spacing for reinforced or unreinforced walls and different weights of roof, loft, or upper stories, a great improvement over traditional adobe rules of thumb.

Survey of Literature

Tests of Earthbag Components

Compressive strength tests by engineering students at two universities showed earth-filled bags to be stronger than wood stud wall construction. Compressive strength & deformation of soil and gravel filled bags were tested in 3-bag stacks, 6 and 9-bag stacks. Deformation limits were shown to be an important factor, but neither test used cured, hardened bags that contained the usually recommended proportions of clay. [9 10]



Shear strength and deformation of bags were tested with loose soil fill without pins. Bags stacked at an 18 degree incline showed improved horizontal shear strength in comparison to those laid flat.[11]
Commercial laboratory testing of 20 cm wide poly bag strips for elongation and tensile strength failed at a tension of 6.9 kN/m, or approximately 470 lbs/ foot. [12]

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[9] Bryce Daigle, *Earthbag Housing: Structural Behavior and Applicability in Developing Countries,* (Kingston, Ontario: Queen's University, 2008) 78-79, 173-174 unpublished master's thesis- 173,174 accessed at http://www.earthbagbuilding.com/pdf/Daigle_Bruce_C_200809_MScEng.pdf 8-23-2010
[10] Dunbar, R.; Wipplinger, L. (2006). "Prism Testing of Polypropylene Earthbags". Unpublished report, West Point Military Academy. http://www.earthbagbuilding.com/Testing/prismtest.htm. Last accessed: July 1, 2008.
[11] K. Matsushima, U. Aqil, Y. Mohri, F. Tatsuoka, *Shear Strength and Deformation Characteristics of Geosynthetic Soil Bags Stacked Horizontal and Inclined,* (web magazine, Geosynthetics International 15:2, April 2008)119- 135

TESTS OF DOMED EARTHBAG BUILDINGS

Vaulted and domed earthbag buildings passed stringent testing in 1993 and 1995 to gain California code approval for a high risk seismic area. 2 domes of local earth and one vaulted building that included 7-10% Portland cement for the vault material withstood live load tests to simulate seismic and snow loads to 200% of code requirements without exhibiting any deflection. No straight-wall segments were tested.[13]

TESTS OF EARTH BLOCK AND RAMMED EARTH MATERIALS

Adobe blocks, compressed earth blocks and rammed earth have been thoroughly tested during the past thirty years at various locations around the world. The chart below is compiled from reports, manuals, and building standards.

ACCEPTED STRENGTHS FOR EARTH BUILDING MATERIALS

DENSITY	As built	Block, rammed earth	1700-2200 kg/ m^3	Minke[14]	
COMPRESSIVE STRENGTH	Blocks	Single unit	5- 50 kg/ cm^2	Minke	
		6 units	≥12.23 kg/cm^2 (≥1.2N/mm^2)	India[15]	Recommended standard
		height/thickness = 1.0	13.26 kg/ cm^2 (1.3 MPa)	NZ[16]	
		height/thickness = 0.4	18.35 kg/ cm^2 (1.8 MPa)		
DEFORMATION	Modulus of Elasticity	Single unit	0.06- 0.08 kg/ cm^2 (600- 850 kg/ mm^2)	Minke	dynamic
TENSILE STRENGTH	Most soils usually 10% of compressive strength		0.025- 0.5 kg/ cm^2 (25- 500 g/cm^2)	Minke	
	Bending	Kaolinite clay	≥1.7 kg/cm^2	Minke	By others
	Bending	Montmorillonite clay	≤223 kg/cm^2	Minke	By others

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12 Reported in Daigle
13 Nader Khalili and Vittore, Phill, *Earth Architecture and Ceramics,* 1998, accessed at www.earthbagbuilding.com/Testing/superadobe.htm
14 Gernot Minke, *Building With Earth,* (Basel: Birkhauser, 2006)21, 32-34
15 International Association for Earthquake Engineering, National Information Center for Earthquake Engineering, *Guidelines for Earthquake Resistant Non-Engineered Construction,* 2004 accessed at www.nicee.org/IAEE_English.php August 23, 2010
16 Richard Walker and Morris, Hugh, *Development of New Performance Based Standards For Earth Building*, accessed at http://www.Dab.uts.edu.au/ebrf/research/earthbuildingstandardnz.pdf August 20, 2010

TESTING

TEST 1: TILT ANGLES

The simplest way to test for the coefficient of static friction between two objects or surfaces is to place one on the other and tilt them until some slippage occurs between the two surfaces. The coefficient of static friction is actually equal to the tangent of the angle at which slippage occurs.[17]

Right: Testing apparatus with barbed wire and two earthbags

MATERIALS

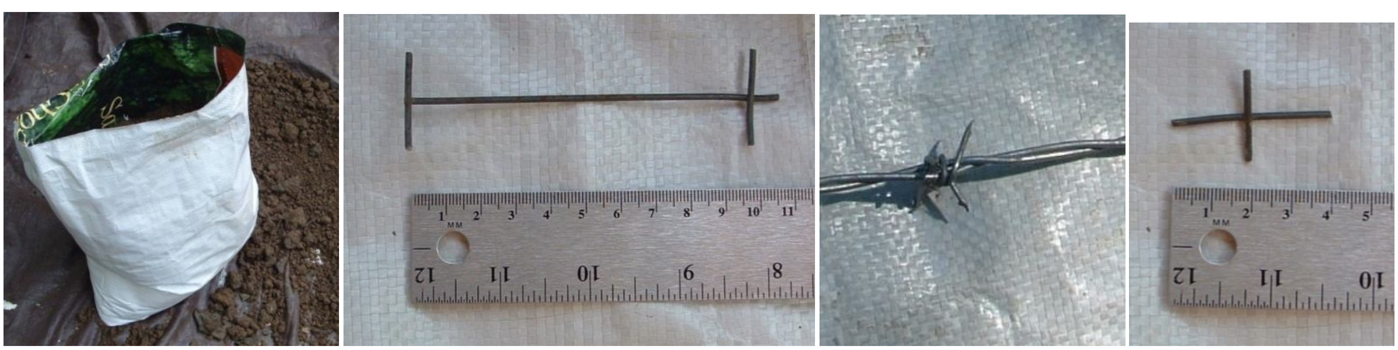
BAGS: Used but good condition 100 pound capacity poly bags were trimmed and sewed to approximate the width of a standard earthbag wall which would be built with 50 pound capacity bags. Bags were turned inside out to expose the untreated surface. After filling, bags were hand-sewn closed. Final size 33 x 40 x 8 cm. One smaller bag (Soil M) was 30 x 33 x 8 cm.

SOILS: Local and regional soils were gathered and evaluated for dry strength and plasticity. Clay soils combined with other soils were broken into clumps, sun-dried, pulverized and mixed. Soil mixes were evaluated with a standard drop test for cohesive strength and dampness before filling bags.[18]

L: sandy mottled blue and warm gray moderate strength silty clay (layer in Lomala creek, Hopewell Junction, NY) slightly plastic
M: smooth strong blue-gray clay (creek bank material near Mill Road, Rhinebeck, NY) very plastic and moderately hard
V: silty moderate strength brown clay (edge of vernal pool, Holmes, NY) slightly plastic
V mix: silty clay V blended with mason's sand and sandy clay L 1:1:1 barely cohesive

MASON'S SAND: Previously opened, damp material.
GALVANIZED 4 POINT BARBED WIRE: 15.5 gage high tensile steel and 12.5 gage low strength steel.
PLYWOOD BASE: 2 cm thick with a 5 x 8 cm wood lip screwed onto the lower edge.
ANGLE MEASUREMENT TOOL: Carpenter's Ace Magnetic Angle locator #25865
WIRE FENCING: Galvanized standard 5 x 10 cm wire mesh cut into small pins of one, two, or more points.
4x4 Timber: Used instead of traditional metal tamping tool.

Right: Mixing soils L and V



Above, left to right: Test bag, 2 point pin, barbed wire, single point pin.

[17] Wikipedia article on coefficient of friction
[18] Patti Stouter, *Soils for Earthbag Part 1: Soil Testing* (ebooklet, September 2010) available at http://www.scribd.com/doc/29252833/Soil-Tests-for-Earthbag

METHODS

Test 1 explored the force necessary to cause individual bags to slide laterally across the barbed wire that functions as mortar. Test 2 explored the force required to cause bags and wire to separate axially.

Earthbags with several different types and qualities of fill were tested repeatedly on five different occasions. Bags were placed on a level board with a lip and tamped lightly. The longer width (38- 40 cm) that approximated the width of a finished wall, was placed perpendicular to the lip. The measuring device rested on the board and its lip.

Right: Tamping bags after placement

Below right: Bags propped at a stable tilt

The board was then tilted gradually until the top bag was seen to slip in relation to the bottom bag. At angles above 50 degrees the measuring tool tended to sit on the lip and had to be held against the base board to give an accurate measurement.

Individual bags were tested multiple times, but wire or pins were always carefully located in undamaged fabric. Barbed wire and several different sizes of metal pins were used between bags. When barbed wire was tested, a single strand was looped to pass over the bottom bag twice for early tests. In later tests when separate strands were used, they had to be anchored by tucking under the bottom bag.

TILT ANGLES RESULTS

Earthbags do not tend to fall off of each other easily if they are carefully assembled with barbed wire between layers. They will rest unsupported at high angles, held in place by either barbed wire or prongs.

Summary:	Individual Test Results Angle at Motion					Average Coefficient of friction
clay bags barbed wire only	57	62	62	62		1.8
clay bags bbd wire & 1 pt pin	65	55				1.7
clay bags bbd wire & 2 pt pin	65	68	68	72		2.5
clay bags no wire & 2 pt pin	70	62				2.2
poorly mixed clay bbd wire & 1 pt pin	62					1.9
poorly mixed clay bbd wire & 2 pt pin	68	68				2.5
Lower friction test results with only barbed wire:						
poorly mixed sandy clay	45	54	53	52	52	1.2
clay bags if wire can roll	45	50	45			1.1
bouncy wet plastic clay	48	50				1.2

Tilt Angles Discussion

The greatest limitation on the accuracy of this type of coefficient of friction test is observer error in trying to assess when movement begins. Static friction limits may be easier to perceive than dynamic, because they relate to the point at which the slightest motion is observed. The coefficient of dynamic friction relates to the point when motion becomes continuous, and is harder to discern.

Earthbags present some unique challenges because their 4 to 5 inch thickness causes a moment arm that becomes apparent at higher angles. Poly bag surfaces without barbed wire begin to slip between 20 and 25 degrees. This motion is immediate and obvious.

Soil filled bags interlaid with barbed wire or pins hold together to an angle between 55 and 70 degrees. The bags usually seem to separate very slightly at about 45 or 50 degrees. At this point the bag fabrics are no longer touching, and all friction is a result of the wire or pins interlocking with the bags and or bag fill. It is likely that this slight shift actually reduces the angle at which motion commences. If so, these test results will underestimate the coefficient of friction of an actual earthbag wall under horizontal loading.

This preliminary separation at high angles could be the reason for the poor performance of softer bag fill. Although different soils were expected to influence the results, only one bag seemed to perform differently because of its consistency. The bags that were more malleable or bouncy when tamped seemed to detach a little more easily from barbed wire before they were cured. But the very plastic clay created a strong bag once it had hardened.

The first bag of V mix did not harden with time. It was more bendable when leaned up against a support. After four days it was sliced open, and revealed a poorly mixed interior. The clay soil had been originally left in 4- 5 cm lumps. When the mix was tamped repeatedly, the clay in the exterior portion of the bag coalesced. But the interior of the bag was composed of unmixed clay lumps inside a loose matrix of sand. The corners were weaker than in the better mixed bag of similar soil. This soil was remixed by breaking up the outer layer, drying in the sun and crushing more finely.

Right: Bag V mix was loose inside after four days

Below right: Characteristic 2- 4 cm tears from jerky bag movement

As long as the bag fill contained enough well-mixed clay to allow the bags to feel somewhat stiff when held up or leaned, and not sag, the exact soil particle sizes seemed to have little influence on friction.

The fullness of the bags, types of pins, and details of wire placement appeared more important than bag fill.

Bag M contained a moderately hard and very plastic clay. An unmixed sample of this clay expanded 30% in a simple free swell test using a test tube. This soil was diluted with 5% sand and 2.5% wood ash before being used in the bag. It is unknown how much this soil shrunk after being placed in the bag and tamped well. (It was later re-wetted and swelled at this point less than 2%). As this clay dried, the bag became slightly loose, and did not perform quite as well in friction testing. It was just loose enough that the dried earth block could be easily pulled out of the bag.

Slightly loose bags from expansive clays may not reduce friction as much when under pressure in a wall. The same bag used in the axial pull-out test under more weight held the barbed wire until the barbs bent (see Test 2).

Tearing of bag fabric did not seem to be a major problem either. It required a significant amount of momentum to cause the slicing of fabric. Usually only one barb would cause tears. The most damaging tests only caused a 4 to 8 cm long cut.

Test 1: Tilt Angles (continued)

Pins were very helpful to stabilize bags at higher angles when they had 2 teeth and were inserted crosswise to the direction of lift. Two bags tilted have a great tendency to rock any connector that is not braced. Straight barbed wire strands running parallel to the wooden lip tended to roll and cause the bags to slip at very low tilt angles. Single point pins tended to allow the upper bag to roll off. It may be less likely for this rolling behavior to be a major factor in bags under more weight or compressed by straps within the matrix of a bag wall.

Pins alone performed very well to increase bag friction. They may be less expensive than barbed wire, but because they do not lend any tensile strength to bag walls it would not be an even exchange to use them instead of barbed wire. Pins also make it more difficult to place bags above. It is easiest to align bag edges accurately when laid on a thin plastic sheet, and sliding them on each other to fine-tune placement. Longer teeth are harder to place a bag on, and thus make the chances of pin or comb rotating flat more likely. Short pin teeth did not reduce the effectiveness of pins to connect bag surfaces.

Pins may be worthwhile to increase the cohesiveness of key structural elements of a building in a high seismic risk region, like piers or corners. But barbed wire appears to be an effective and important part of the structural system.

Future tests could recheck whether cured bags or more heavily tamped bags exhibit a higher coefficient of friction. A trial of thinner earthbags might also be helpful to examine whether coefficients of friction are actually higher than tests with 10 or 12 cm bags might indicate.

Left: Pins laid perpendicular to the direction of tilt stay embedded in bags

Test 2: Axial Pull-out

Pulling or pushing force can be measured directly with a lever and a household scale or a makeshift heavy spring scale. The same bags with wires were retested for the force required to remove the wire.

Materials

EARTHBAGS: Clay M and Clay L, cured for 2 weeks
SPRING: Steel spring 26.5 x 2.3 cm
DIGITAL BATHROOM SCALE: Healthometer model HDL 110 T248BN
TAPE MEASURES, SPACKLE BUCKETS, CHAINS & CARIBINERS

Methods

The axial force needed to pull barbed wire out from under bags was measured on two occasions. Two strands of 15.5 gage barbed wire were laid between two firm bags, with three barbs engaged on each strand. After a second bag was laid on top, the upper bag was tamped lightly.

Then an additional 4 bags were added to simulate the weight of a concrete bond beam or strapping uniting three courses of bags in an alternative bond beam. These bags added an additional 137.5 pounds above the wire.

A lever system was used first to test for static friction levels. The tension was released as soon as slight motion was detected. The barbed wire was found to still be firmly anchored after some slight motion.

Test 2: axial pull-out (continued)

A simple spring functioned as a scale on the tests for kinetic friction later. The maximum length of the spring was measured as the wire pulled out. Then the spring was hung vertically and weight added until the spring extension matched that measured when pulling the wire out from the bags. Finally the weighted buckets were weighed on the digital scale.

The exact extension of the spring before complete pull-out was difficult to perceive because the wire moved quickly once the barbs gave out. A video camera supported on a frame over a very firmly attached ruler would be helpful.

Because this test was performed on bags that cured on the wire, and it deformed the barbs it has so far only been performed twice.

Right: Weighted buckets caused extension of the spring

Below right: Deformed barbs all bent in the same direction

Results

The tests for static friction limits returned forces of 60 – 80 pounds for 3 four point barbs (spaced 12 cm apart).

For kinetic friction limits between cured bags, the forces were very uniform, at 117- 119 pounds.

Discussion: Axial Pull-out

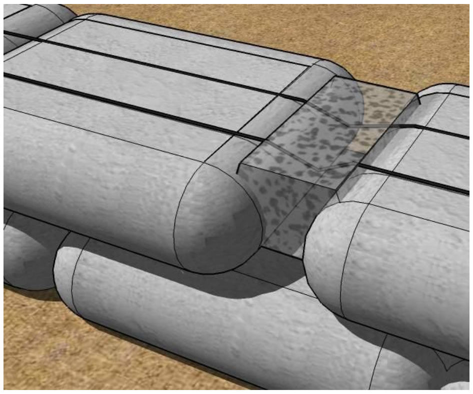
Instead of tearing the bags, all of the embedded barbs appeared to have bent.

It is not known whether the barbs on low-tensile strength 12.5 gage barbed wire are stronger. The low-tensile strength wire costs approximately twice as much as the newer high-tensile strength 15.5 gage barbed wire. It is heavier and somewhat harder to handle.

2 point barbed wire might show less resistance to axial forces. Future tests should explore the performance of heavier wire and of 2 point barbs.

Although horizontal forces act laterally on a wall, tension acting at a slight angle can greatly increase the effective force. This would happen at the attachment point or building corner if the center of an earthbag wall between shear walls deforms slightly. Extra reinforcing might be helpful at these points.

Two different techniques could be used to reinforce the wire connection at stress points like corners, bracing elements, buttresses, or piers. Cement mortar can be used in spaces between bags to bond with barbed wire above and below and form an anchor. Or additional pins could be used at critical locations and tied to wire.



Above right: mortar anchors between bags

Right: Metal pins to anchor wire

Summary

Barbed wire contributes to both the friction (related to shear strength) and the tensile strength of earthbag walls. Mr. Khalili chose wisely when he decided to interlay the two materials.

For unreinforced geo-cell retaining walls the upper bound seismic coefficient should be about 0.4 x Peak Ground Acceleration, and for reinforced geo-cell walls, 0.3 x PGA. Peak ground acceleration considered for seismic design is usually rated as below or above 0.6 m/second. Using a factor of 0.5 x PGA for a 0.6 m/ second location would require a coefficient of friction of at least 1.2.

Only an improperly anchored barbed wire that allowed rolling was slightly lower at 1.1. Earthbags that were obviously not tamping firm were near this figure. But all the bags that tamped firm and did not allow rolling on the wire performed at 40% to more than 200% this level of friction.

Traditional formulas for bending moments acting on walls may not truly reflect the inertial stability of a thick wall system with high coefficients of friction between layers. Two engineers involved in the New Zealand standards consider that more testing is needed to reflect the contributions of inertial stability to an earth building.

Since tensile strength is low in earthen building materials, the tensile strength of barbed wire can also be vital to earthbag building stability. The matrix of 18- 20 courses of bags with 2 strands of wire each in a single story earthbag building can transmit significant horizontal forces.

A force of 120 pounds per each 3 barbs or 15 inch length can total approximately 1550 pounds force per wire. The tensile strength of barbed wire is 950 pounds for 12.5 guage and 1500 pounds for cheaper and lighter high-tensile wire.

If the tensile strength of the wire is the limiting factor, at 1900 pounds per course (using the conservative value of 2 strands of the weaker wire) a 5m length of earthbag wall between bracing supports would contain wire capable of supporting 34,000 pounds. For walls interrupted by a 1.2 m height window, the continuous wire above and below the window could support 17,000 pounds.

Earthbag walls weigh approximately 4400 pounds per linear meter. A 5 m section of wall with a 1m by 1.2 m window weighs approximately 20,000 pounds. With a mesh containment layer added to reinforce the plaster tensile strength may approach a safe factor of safety for earthbag walls.

APPENDIX 1

TEST 1 DATA: TILT ANGLES INDIVIDUAL TESTS

	8-13-2010	# reinf	depth top teeth cm	depth btm teeth cm	# teeth w. bbd wire	average angle @ first motion	C_f	comments
	newly tamped bags & barbed wire; bottom bag: V clay; top bag: V mix (poorly mixed)							
1	Control: no barbed wire	0	na	na	0	22	0.4	slipped and continued
2	2 strands barbed wire	0	na	na	6	45	1.0	moved too quickly, upper bag slumped, slit bag 8- 12 mm
3	2 strands barbed wire	0	na	na	6	54	1.4	moved more slowly, lower and upper bags not damaged
	8-16-2010							
	bottom bag: V mix (poorly mixed); top bag: V clay							both bags wet
1	control: only barbed wire	0	na	na	6	57	1.5	moved slowly, upper bag did not move out, no damage
2	1 cross + barbed wire	1	4.0	9.0	7	65	2.1	not too hard to insert perpendicular
3	1 cross alone	1	4.0	9.0	1	50	1.2	gave by rotation- hard to insert perpendicular
4	1 cross alone	2	1.0	1.0	2	70	2.7	easy to insert, started rotation instead of tearing bag
5	2 pins @ 2 teeth, crosswise to lift, at edges of bag	2	4.2	4.2	4	75	3.7	moved from board but did not slip
6	1 pin @2 teeth, crosswise to lift, centered	1	4.2	4.2	2	62	1.9	
7	1 comb @ 5 teeth, crosswise to lift, centered	1	4.2	4.2	5	75	3.7	hardly moved at all, no slipping
8	1 comb @ 5 teeth, diag to lift, centered	1	2.0	2.0	5	72	3.1	gave by rotation- hard to insert perpendicular
9	straight pins in bottom bag	2	4.0	0.0	2	low 20s		slid into bottom when top placed
10	straight pins through bag edge	4	1.0	5.0	4	48	1.1	only 2 of 4 held in bottom bag- but tore fabric
11	pins tapped through top bag	2	3.0	7.0	2	42	0.9	gave by rotation

Test 1 Data: Tilt Angles (continued)

		# reinf	depth top teeth cm	depth btm teeth cm	# teeth w. bbd wire	average angle @ first motion	C_f	Comments
	8-17-2010							
	bottom bag: V clay; top bag: V mix (poorly mixed)							bags drier used other unmarred sides
1	control barbed wire only	0	na	na	6	53.0	1.3	lifted off lower bag @ 50 degrees
2	bbd wire & cross	1	1.0	1.0	7	62	1.9	slid at 65
3	bbd wire & 2 point pin	1	1.5	1.5	8	68	2.5	
4	bbd wire & 2 point pin	1	4	4	8	70	2.7	
	bottom bag: V mix (poorly mixed); top bag: V clay							
5	control barbed wire only	0	na	na	6	52	1.3	moved at 52, slid at 62
6	bbd wire & pin w 2 teeth	1	1.5	1.5	8	66.5	2.3	slid at 68 and 70
7	bbd wire & pin w 2 teeth	1	4	4	8	68	2.5	slid at 70
	Separate barbed wire strands; top bag: L clay; bottom bag: V clay							
8	control- barbed wire only	0	na	na	6	46.7	1.1	rolled and caused failure at lower angle
9	bbd wire & pin w 2 teeth	1	1.5	1.5	8	70.0	2.7	slid at 70 first time
10	bbd wire & pin w 2 teeth	1	4	4	8	72	3.1	moved at 72 didn't fail
11	bbd wire & top pin	1	15	na	7	55	1.4	really moved @ 65
	8-17-2010							
	bottom bag: V mix (poorly mixed); top bag: V clay	0	na	na	6	62	1.9	used new 12.5 gage barbed wire
	M Clay on L Clay	0	na	na	6	48	1.1	clay L bag not tight both bags bouncy
	L Clay on M Clay	0	na	na	6	50	1.2	clay L bag not tight both bags bouncy
	V mix (well mixed)	0	na	na	6	62	1.9	tamped firm bags little looser than previous days'
	9-2-2010							
	bottom bag: V clay; top bag: M clay- dried firm							used new 12.5 gage barbed wire
		0	na	na	6	62	1.9	