EARTH WALLS DEFYING EARTHQUAKES

Patti Stouter
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Build Simple Inc.,
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Above: Edge of 7 school building by Architecture for Humanity

Mud buildings kill.

Let's be clear: traditional earthen buildings kill people in earthquakes. This happens when sideways pushing forces overcome low flexing strengths of unreinforced earthen walls.

But cheap and sustainable earth site walls of geo-textiles excel in quake zones. So it makes sense that earth can hold up in buildings too, with a little help. An integrated 3-D grid of strong fabric with a little steel multiplies earth's strengths.

Dozens of earthbag (also called contained earth) buildings survived[1] Nepal's 2015 quakes where destroyed villages underwent as much as 0.75 g forces[2].

WHAT IS CONTAINED EARTH/ EARTHBAG?

Start with fabric surrounding earthen fill. Add short buttress stub walls as bracing. Make strong corners. Finish with interconnected wire and rebar to hold wall materials together after the quake passes

Bags or tubes of non-biodegradable poly fabric or mesh serve as a flexible form while damp soil is tamped in place. Cured soil containing clay hardens around barbs of inter-layered barbed wire. Underneath may be the cheapest base isolation known to man: strapped gravel bags that act like brakes with friction levels that increase under stress.

Contained earth walls look like most other masonry buildings. Mesh-reinforced stucco or plaster finishes protect the bag or tube fabrics from UV. The easily replaceable surface plaster breaks first in seismic events and delays wall structural damage.

The cost? Wisdom, care, and sweat equity may be more critical than cash investment for buildings made of 97% local natural materials.

Earthbag walls often cost 60- 50% less than concrete block walls in the developing world.

[1] Geiger 2015, Nordquist 2015

[2] United States Geological Service (7/2/2015). M7.8 - 36km E of Khudi, Nepal; Peak Acceleration Map in %g [online], compared to locations of surviving buildings east and northeast of Kathmandu and southeast of Dolalghat.

WHAT ISN'T CONTAINED EARTH?

Sandbags aren't.

Soil bags aren't.

Dirtbags aren't.

Gravel bags are useful- but they aren't contained earth.

The fill is the key. Contained earth (CE) is a wall (and/ or roof) system using soil that is:

1. COHESIVE (ABLE TO STICK TOGETHER)
2. DAMP
3. TAMPED
4. CURED

HIGH QUALITY CONTAINED EARTH WALLS

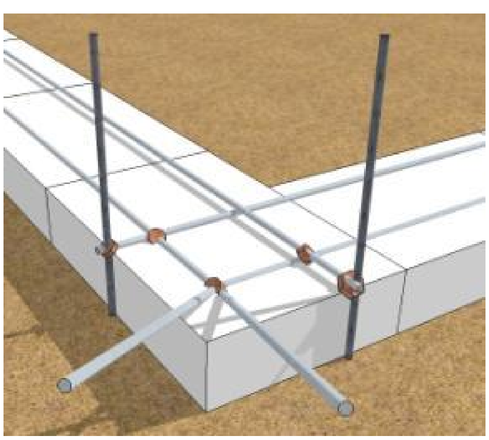
Many soils can be used, but the stronger the soil, the stronger the wall.

Hat and boots: roof overhangs and a water-resistant base protect earthen walls from water. Contained gravel can form a strong water-resistant wall base. If gravel is not available a small proportion of cement or lime can stabilize the earthen fill in the first few courses against damage from soaking.

Chemicals like Portland cement are usually not needed to strengthen soil.

Good tamping compacts fill about 20% and increases strength.

Above: Damp, cohesive soil fill compacts when tamped



Reinforcement can include half lengths of rebar hammered into moist walls. Better yet, barbed wire can be attached to whole rebars spanning from the footing to bond beam at wall and buttress ends.

Left: High strength corner reinforcement

A strong bond beam is always needed on an earthen wall. It can be made of lap jointed doubled lumber, or poured as reinforced concrete.

High quality CE has the right amount and type of reinforcement for the local level of risk and the type of containing fabric.

Solid CE

- mesh tubing
- walls go solid between courses
- barbed wire is recommended
- better shear strength
- little potential for vibration damping
- plaster may stick easily
- a.k.a. Hiperadobe

Right: BSI test wall of solid CE with barbed wire attached to anchored exterior rebar.

Modular CE

- solid-weave tubes or bags
- barbed wire is critical
- lower shear strength
- some potential for vibration damping
- stucco will need a strong mesh
- a.k.a. Superadobe, conventional earthbag

Right: Rebuilding in Nepal, Steadfast Co.

What Do We Know About CE Strength?

Most laboratory testing to date with earthbag in the title actually tested contained sand (CS). The earthen fill was either not cohesive (U Bath studies[3]), not damp enough or cured well (U Florida study[4]) or not tamped.

Fill and reinforcement attachments are much stronger when fill is well dampened and tamped. Strong fill is stronger than the containing poly bag.

CE units were tested under compression as single units at Queens University[5] and the University of New Mexico[6] and in bag stacks at Dartmouth College[7].

Doubled bags have been tested in a shear box (of poor strength soil) for friction without barbed wire at the University of Bath[8]. The low result of 0.43 was matched by BSI's simple tilt table tests for strong cured soil without barbed wire. BSI tilt tests revealed a range of static friction

CE Compressive Strength

100- 600 PSI UCS

CE Elasticity

20 MPA

Static Friction between Poly Bags

0.43

CE Static Friction with Wire

1.2 WEAK/ UNTAMPED

1.7 STRONG FILL

2.2 STRONG + PINS

CE Pull-out Force per Barb

20 LB UNCURED

27 LB CURED 2 DAYS

40 LB FULLY CURED

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[3] Vadgama, p 20

[4] Ross et al, p 535 Although he describes the soil as a silty-sand, it would not compact as much as his photos show unless the soil also contained some clay. He notes that it lacked desirable cohesive properties. p 536 it was assembled, tested and disassembled within a 2-week period- not enough time for any curing of the 36 cm thick wall.

[5] Daigle, 2008 p 27

[6] Witnessed by the author

[7] Malik, 2013 p 9

[8] Vadgama, p 38

PLASTERED CE:

Modular Shear Strength

>8.8 KPA/ 184 PSF

Modular Rigidity

0.012 GPA/ 1700 PSI

UNPLASTERED CE:

Modular Out- of-Plane Strength

5.3 KPA/ 111 PSF UNREINFORCED

6.4 KPA/ 230 PSF REINFORCED

provided by barbed wire in strong and weak soil and additional 3 cm wire pins[9].

BSI completed 3 pull-out tests of barbed wire between cured and partly cured CE units[10].

BSI tested CE wall portions statically in 80% scale for shear strength and modulus of rigidity[11].

Below: BSI's strong soil wall after shear testing

BSI also tested a series of 60% scale wall corners for out-of-plane and corner strength[12].

Dartmouth students tested 40% scale walls for out-of-plane and shear strength. These figures were within 20% of BSI strength findings when adjusted for sample size[13].

Dartmouth students also completed a series of 1/6 scale corners for vibration resistance.

[9] Stouter, 2015 p 14

[10] Ibid, p 15; with added normal force of 200 lb.

[11] Stouter 2014, p 12; one 1,8 m² (19.3 sf) wall built of strong soil with 1 inserted rebar, plaster on mesh, and 2 strands barbed wire per course, was only slightly damaged when the testing frame failed.

[13] Conolly et al, 2012 p 20; two ±0,14 M² (1.5 sf) wall walls with barbed wire and plaster, fully cured. Tested to 1/30 deformation

Despite the small scale and their inability to convert acceleration readings to displacement, these small shake tests showed that adding buttresses to a corner reduced motion by 26%. Adding a solid mass between 2 buttresses at the corner reduced motion by 33% and prevented damage to the wall. Using Solidworks software for FEM analysis, considering the barbed wire barbs as independent pins allowed a modeling accuracy of ±1.5%.

UNPLASTERED CE:

Solid Out- of-Plane Strength

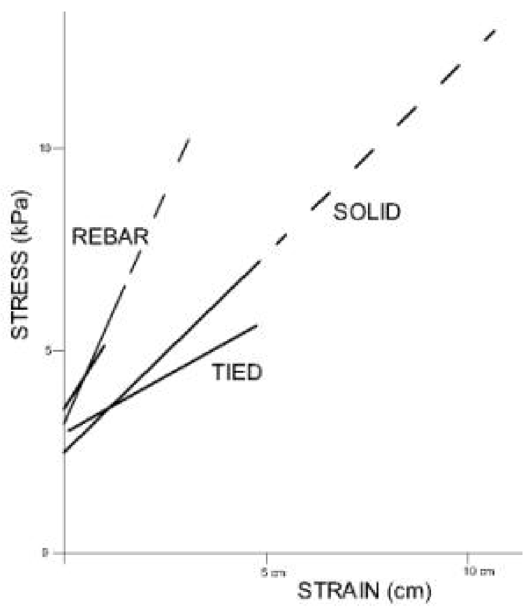
12.8 KPA/ 267 PSF

UNREINFORCED

Rigidity

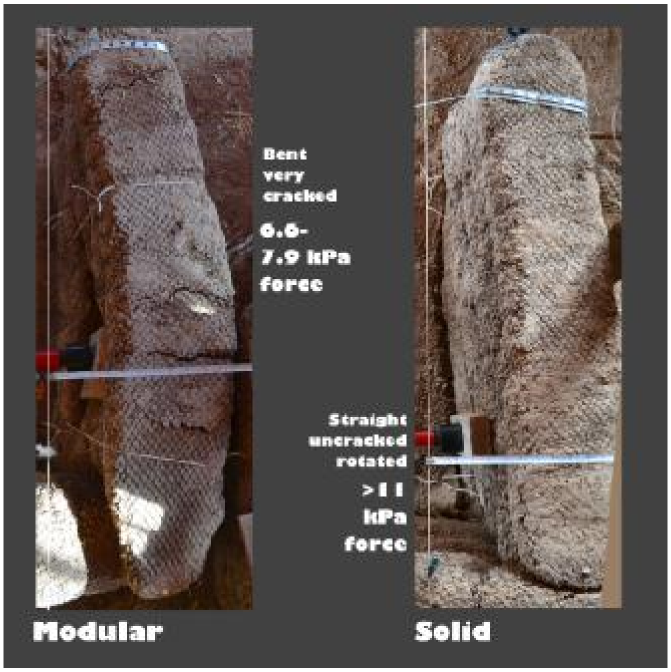
0.0000067 GPA/ 0.97 PSI

BSI's test of corners included solid CE, which showed strengths twice as high as modular. One solid CE wall was retested with bracing as a true out-of-plane test[14]. Very helpful results came from comparing the linear portions of the deformation per force graph of these 8 walls (see below).



OUT-OF-PLANE ULTIMATE STRENGTH FOR STRONG SOIL FULL-SCALE WALLS (STOUTER, STRONGER EB CORNERS)	kPa (psf) for 1,34 m (4.4') bracing
Solid CE Unreinforced Wall	20 (418)
Modular CE with Inserted Rebar	9 (188)
Modular CE with Barbed Wire Tied between Courses at Corners	9 (188)

[14] Stouter unpublished report Stronger Earthbag Corners, one wall section was braced to create a 0.42 M² (4.5 sf) span



Above: BSI tests of 60% scale wall corners compared walls solidified between courses with modular construction (not solidified between courses)

BSI also completed a series of shear box tests on contained gravel (CG) which is often used as a base wall for CE. These tests of 4 full-size bags showed kinetic friction consistently significantly higher than static friction.

Kinetic friction 1.3- 2.8 times higher than static values indicate potential as a vibration damping medium.

Tests of double bag stacks at Hiroshima University under 25 Kn (5600 lb) normal force stopped vibrating in less than a second after 0.1 g acceleration forces were removed[15]. This shows potential vibration damping to reduce the transmission of vibrations from a building site to the building walls.

[15] Yamamoto and Cheng, 2012, pp 4-5

UNPLASTERED CG FRICTION:

Bags on Rubble

0.32- 0.81 STATIC

0.67- 1.11 KINETIC

Bags on Bags with Barbed Wire

0.45- 0.57 STATIC

0.56- 0.72 KINETIC

VIBRATION DAMPING:

Bag stacks

H= 0.16 EIGEN FREQUENCY

6.5 HZ

PLASTERED CE:

Shear Strength

MODULAR: ?

SOLID: ?

Out-of-Plane Strength

MODULAR: ?

SOLID: ?

Vibration Damping Potential

MODULAR: ?

SOLID: ?

STUCCOD CG:

Shear and Out-of-Plane Strength

Vibration Damping

What Do We Need to Learn?

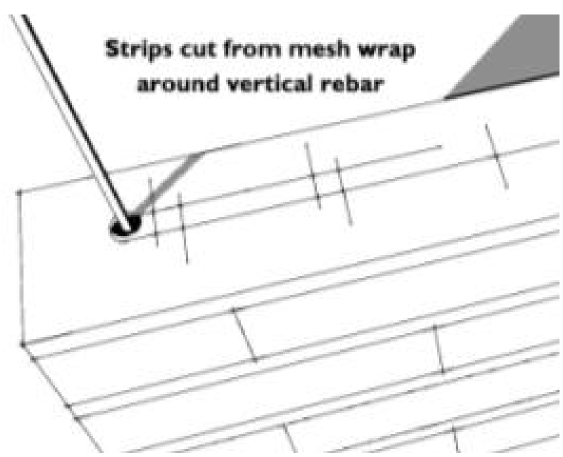
Full-scale CE walls need testing in cyclic dynamic or vibrational stress- solid and modular versions with different soil strengths and different types of reinforcement.

Strong soil, good detailing and careful plans will save lives- after engineers can give builders simple but accurate guidelines.

Adobe guidelines may provide a starting point, since earthbag builders have successfully used height to thickness ratios and bracing walls similar to adobe.

New Zealand's plan limits, sound details, and bracing wall requirements provide seismic load resistance in each principal direction of the building[16].

Adobe in New Zealand's highest seismic risk area needs five layers of horizontal mesh strip wrapped around vertical rebar in each single story wall. One D12 (half inch) rebar is spaced every 1.35 m (4' 5") for 28- 35 cm (11-14") thick walls



Right: Mesh strips of 5.3 mm (4 ga) welded wire mesh on 15 cm (6") centers for New Zealand

[16] Walker, Morris, p 6

COMPARING SHEAR STRENGTH OF REINFORCED EARTHEN WALL PANELS

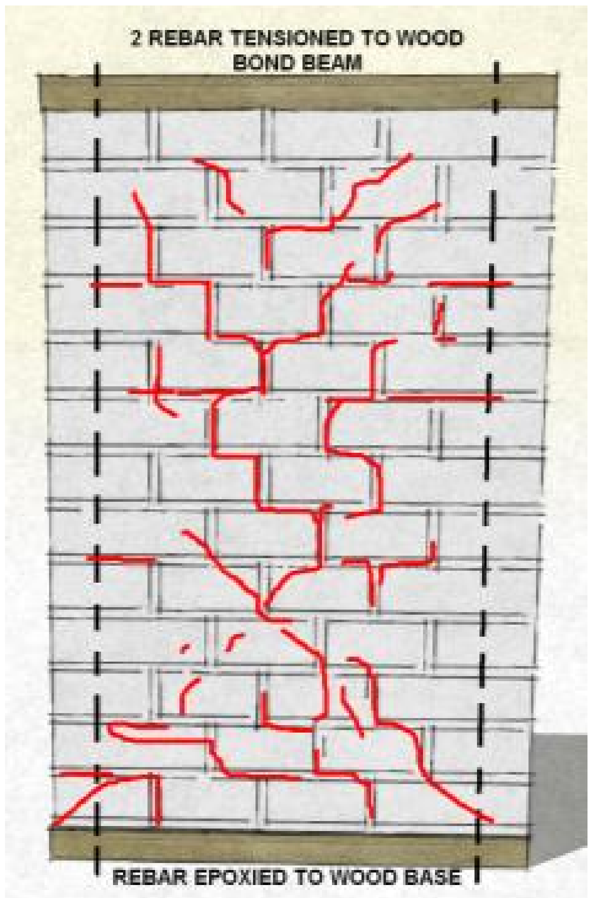
	BSI Strong Earthbag Wall	NZ Reinforced Adobe[17]
Strength:	8,8 kPa (188 psf) Static shear slight damage	11,9 kPa (249 psf) Cyclic shear ULS
Wall height:	1,24 m (49”)	1,8 m (71”)
Wall area:	1,8 m² (19 sf)	2,2 m² (23sf)
Wall thickness:	30 cm (12”) 80% wall thickness	26 cm (10”)
Reinforcement:	Horizontal: 2 barbed wire/ course Vertical: 1 D16 (5/8”) rebar inserted, not anchored top or bottom No bond beam Plaster: earth on medium strength plastic mesh	Horizontal: wire mesh strip with teeth set in mortar every other course 3rd and above, wrapped around rebar Vertical: 2 D12 (1/2”) rebar pre-tensioned Wood bond beam No plaster

2.7 m (8’ 10”) high[18]. The vertical rebar is a single piece, anchored in concrete footing and tensioned to a bond beam[19].

Rebar in contained earth has usually been inserted in several separate lengths, not anchored at the base. Researchers have compared this type of rebar to a composite beam. The rebar acts as a flange in tension and the bag halves between the steel and the pressure act with it as a compression flange. It is stronger than the steel rebar alone, weaker than an equivalent steel beam (Croft, pp 37- 38).

BSI static tests of an almost intact earthbag wall without anchored rebar or bond beam were within 75% of New Zealand’s recorded cyclic strength of more highly reinforced adobe. The full strength of contained earth must be compared.

It’s time that safe and sustainable geo-textile walls begin to spread where earthquakes threaten.



Right: Reinforced adobe wall after cyclic dynamic testing

[17] (Morris, Walker, 2000, p. 7) graph and (Morris, 1992, p. 668- 669)
[18] Standards New Zealand, 4299, p. 58
[19] Morris, Walker, Drupsteen 2011

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