Review of Earthen Building Codes and Standards from Around the World

Bruce King, PE

Abstract

A large number of earthen building codes, norms, guidelines and standards have appeared around the world over the past few decades, along with a considerable amount of research and field observations regarding the seismic performance of earthen structures.

This paper presents a review and summary comparison of extant codes and standards in terms of content (methods of earthen building covered, material properties, tests, and quality control, and engineering design and retrofit criteria), and style (clarity and method of presentation, presence or absence of commentary or clarifying notes and details). The paper will also review these documents in terms of consistency with current knowledge about seismic design and behavior of earthen structures, and emerging understanding of building science and moisture issues. Also considered will be the range of perspectives represented in terms of local seismicity, climate and rainfall, and affluence (affordability).


Introduction

The oldest extant structures to be found on Earth—in Mesopotamia, Arabia, the Mediterranean, India, and China—are of earthen construction, and date back thousands of years. Earth is in that sense the oldest building material, and remains to this day the most widespread in that a very large percentage of the world’s population sleeps every night in an earthen dwelling. With an increasing number of exceptions, that is because earthen walls (and sometimes domes and vaults) are all that people can afford, thus the deeply-rooted association of “mud huts” with utter poverty. The past two hundred years of the Industrial Revolution has hardened and, perversely, enshrined that perception such that few people in the developed world would consider living or working in an earthen structure. Worse, in many areas of the world it is becoming difficult if not outright illegal to build with earth simply because of its omission from, or poor treatment in, building codes and standards.

Over the past several decades, two trends have begun to change that. One is simple philanthropy: those that are able and willing have been expanding our understanding of earth as a building material (both with and without various types of stabilizers) and our understanding of how earthen structures behave under seismic loads, moisture abrasion and intrusion, and other such annoyances. The other trend is the rapidly growing interest in sustainability, a worldview which can loosely be described as requiring due consideration for the other species with whom we share the ecosphere, and like consideration for far distant generations of humans who will inherit the works of this one. Seen through the lense of sustainability, earthen construction takes on a brand new and compelling allure, for it is about as “green”—which is to say, unobtrusive—as building can get.

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There are many ways to build with earth. Seen from a broader perspective, there is in fact nothing else—except for snow igloos—to build with besides earth, modified or stabilized by one process or another. This is more than a trivial point, in that it suggests the question, for any building project: “How much and by what means do we stabilize earth to get the building performance we want?” The world has many thousand-year old cob or adobe structures whose existence demonstrates that clay alone can be plenty of binder and stabilizer, while, conversely, the periodic mass deaths of thousands in floods, hurricanes and earthquakes demonstrates that often clay alone (or poorly-built concrete) is not enough. Reinforced concrete, a specialized form of earthen construction, is enormously versatile, utilitarian, and widespread, yet codes governing its use often mandate strength well in excess of that needed—or are rendered pointless for lack of enforcement. A well written building standard will recognize all of this. In any case, “earthen construction” will hereafter be used as generally understood, and refer to the use of minimally amended or unprocessed soil in building structures.

Historically, adobe (unfired clay brick), rammed earth (dampened soil packed in layers between formwork), and cob (or puddled earth—moist clumps of dense straw-clay packed and sculpted by hand) are the predominant methods for building both residences and grand structures such as the Step Pyramid at Saqqara, Egypt, the Grand Mosque in Djenne, Mali, or Taos Pueblo in New Mexico, USA.

In modern times, adobe and rammed earth are joined by compressed earth blocks as the three predominant earth building systems, and thus the main focus of extant earthen construction standards. It is worth noting, however—as many standards do—that historical systems such as cob and straw-clay infill are still common in parts of the world, and enjoying a modest renaissance in the developed world. New systems such as mechanically sprayed soil or soil-cement, earth-filled tubes, tires and bags, and poured earth stabilized with calcined gypsum (among others) are being developed. Most of these revived or new systems amount, to date, to no more than a marginal part of earthen building, and thus as yet do not compel much testing or attention in earthen construction standards. They are, nonetheless, better understood and accepted as a result of recent testing and standards development for the predominant systems.

As noted, earthen construction has been around a long time, and was for most of history, in many areas, the only material available for erecting walls or vaults. That remains true for the poorer areas of the world, be they nearly-entire countries such as in Africa, Asia or Latin America, or the pockets of poverty that occur within and around the world’s growing cities. This has, again, hardened the impression among both rich and poor that earthen construction is only for the lowest classes. Earthen construction standards generally and appropriately reflect this in that they seek to identify prescriptive requirements for materials and construction that do not raise the price of creating a new home any more than absolutely necessary. Doing so requires that these standards recognize the many and high variabilities—within a single structure, and between neighboring communities—of the quality of design and construction, the types of soil used, and the degree of maintenance provided over time. As such, prescriptive standards tend to be (necessarily) quite conservative, resulting in more and thicker walls, and fewer openings, than a well-engineered design might produce.

Still, our understanding of how best to build with earth has grown tremendously in the past few decades. A great deal of testing has been done, both in laboratories and in the field, of soils and their properties, soils combined with stabilizers, wall assemblies, reinforcing materials and systems, and entire structures. A cursory review of the available literature shows that testing to be primarily structural, particularly and appropriately focusing on seismic loading, and to a much lesser extent on the thermal (insulation) properties of earth walls, and on the effects of moisture in all its forms on earthen construction.

As is the case with codes and standards in general, this obsession with seismic design, while understandable, has sometimes made for a certain blindness to the very real and related effects of moisture. For example, many codes allow or even prescribe cement-based plasters despite the well-known deleterious effects of those plasters on unstabilized earth walls, and despite the known fact that lime-cement plasters—an inexpensive substitute—provide plenty of strength and durability while allowing enough vapor permeability to prevent the trapping of moisture within the wall. Likewise, both testing and historical experience have shown that inexpensive plant fiber reinforcing such as bamboo, cane or burlap can greatly improve the seismic strength and ductility of ordinary adobe buildings. But the extra cost and effort of installing
cellulose-based reinforcing is lost without comparable attention to moisture detailing. Everyone knows that a wet earth wall is a weakened—and thus hazardous—earth wall, and that wind-driven rain on an unprotected wall will erode it. But little consideration is given to the fact that plant-based reinforcing installed to resist a once in 100 or 500 year earthquake is of little value if it has essentially rotted in a thirty-year period. An easy solution to this problem, of course, is to use a stiff plastic reinforcing such as geotextile fabric, but such materials are far too expensive, if even available, to those who most need them.

As our knowledge about earth engineering has grown, earthen building has seen a small but distinct renewal in the industrialized world, and people who are more than affluent enough to build with anything they may want are choosing to build with earth. This renewal, occurring in many industrialized countries around the world with the advent of the sustainability perspective, is manifested by a few commercial and religious buildings, as well as a plethora of mid and high-end residences.

In light of all these recent developments, earthen construction standards to date have tried in various ways to keep earthen building affordable while making it safer, and at the same time address the far more demanding building performance expectations of the industrialized world. We now know a lot about how to build well with earth, but most of the people who do so just can’t afford to, or don’t have access to the best information, or sometimes just won’t change. This dilemma—both recognized and brushed aside in many of the standards and commentaries—is by no means easily resolved. It is, nevertheless, integral to the concept of sustainability and the preservation of earthen architecture, and as such forms much of the context within which extant standards are reviewed in the pages to follow.

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*a cement-stabilized sprayed earth bath house for disabled children near San Francisco, California in a very high seismic risk area*

photo courtesy of J. D. Peterson
References  (documents reviewed in this paper)

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Norm, Code, or Standard / [country of origin] / date released</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM</td>
<td>American Society of Testing and Materials  E2392-05  [USA]</td>
</tr>
<tr>
<td>ARIZ</td>
<td>Uniform Administrative Code Amendment for Earthen Material and Straw Bale Structures, Tucson/Pima County, Arizona [USA], 1997</td>
</tr>
<tr>
<td>AUST</td>
<td>The Australian Earth Building Handbook, 2002</td>
</tr>
<tr>
<td>CA</td>
<td>California [USA] Historical Building Code, [USA] 2001</td>
</tr>
<tr>
<td>IBC</td>
<td>International Building Code, [USA] 2000</td>
</tr>
<tr>
<td>NEP</td>
<td>Nepal National Building Code / Mandatory Rules of Thumb / Load Bearing Masonry, 1995</td>
</tr>
<tr>
<td>NM</td>
<td>New Mexico Adobe and Rammed Earth Code, [USA] 2004</td>
</tr>
<tr>
<td>NZ97</td>
<td>New Zealand Standard, Engineering Design of Earth Buildings, 1998</td>
</tr>
<tr>
<td>NZ98</td>
<td>New Zealand Standard, Materials and Workmanship for Earth Buildings, 1998</td>
</tr>
<tr>
<td>NZ99</td>
<td>New Zealand Standard, Earth Buildings not requiring Specific Design, 1998 (including amendment #1, December 1999)</td>
</tr>
<tr>
<td>PERU</td>
<td>National Building Standards Technical Building Standard NTEE.080, [Peru], 2000</td>
</tr>
</tbody>
</table>

Known documents not reviewed in this paper

**CHINA**
The Chinese national building standards devote less than two pages to earthen construction—primarily lime-stabilized and unstabilized earth blocks, presumably because those are the most common methods. The standards provide only the simplest of guidelines, but, unique among all the earthen building standards, provide some guidance (in terms of dimensional restraints) to carved earth construction. This is an historic system (in parts of China, as well as India and Mesopotamia) of carving cave dwellings into soft, semi-cemented tuffaceous soils.

**ECUADOR**
A fairly detailed Ecuadorian standard in development was reviewed, but this author’s limited Spanish prevented a proper assessment. Similar to the Peruvian standard, and detailed in its attention to seismic issues (zones of risk, occupancy importance, foundation soils, etc.), that standard appears to be a fairly sophisticated and useful document for its culture and common building practice.

**GERMANY**
A German earth building standard, now at least 40 years old, is not available in English and, in any case, is not much used (according to German engineers working with earth with whom this author has spoken).
### Brief description of reference documents

<table>
<thead>
<tr>
<th>Reference Document</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM</td>
<td>A short and very general document describing different earthen building systems, primarily aimed at re-introducing them to the “developed” world in the context of sustainability and energy efficiency. (6 pages)</td>
</tr>
<tr>
<td>ARIZ</td>
<td>Prescriptive guidelines for earthen structures, in some parts general, in others very specific, for Pima County (a low seismic risk area). (15 pages)</td>
</tr>
<tr>
<td>AUST</td>
<td>A highly detailed and well-illustrated guide to construction and engineering design of earthen building in general, and the predominant systems in specific. This is not formally adopted by Standards Australia, nor written in the format of a standard, but SA is a primary sponsor and co-author (with Dr. Peter Walker) of the text. (152 pages)</td>
</tr>
<tr>
<td>CA</td>
<td>Prescriptive guidelines and design (retrofit) criteria for adobe, stone masonry, and other “historic or archaic materials” structures (high seismic risk areas). (3 pages)</td>
</tr>
<tr>
<td>IBC</td>
<td>Prescriptive guidelines and minimum strengths for adobe structures. (3 pages)</td>
</tr>
<tr>
<td>IND</td>
<td>Prescriptive guidelines and extensive details covering adobe, cob, rammed earth and Assam (wattle and daub). (low to high seismic risk areas). (12 pages)</td>
</tr>
<tr>
<td>NEP</td>
<td>Prescriptive guidelines and extensive details covering only stone masonry with cement and/or earthen mortars. (high seismic risk areas). (22 pages)</td>
</tr>
<tr>
<td>NM</td>
<td>Prescriptive guidelines and extensive details covering adobe, compressed earth block, and rammed earth. (moderate seismic risk areas). (30 pages)</td>
</tr>
<tr>
<td>NZ97</td>
<td>Methodology for engineering design of earthen structures, derived largely from concrete and masonry procedures, and adjusted based on historical experience and testing with earthen buildings. (56 pages)</td>
</tr>
<tr>
<td>NZ98</td>
<td>Highly detailed and well-illustrated guidelines for material selection, stabilization, testing, and construction quality control (both field and laboratory tests). (81 pages)</td>
</tr>
<tr>
<td>NZ99</td>
<td>Highly detailed and well-illustrated prescriptive guidelines covering adobe, stabilized adobe, compressed earth block, rammed earth, cob, and poured earth. (moderate to high seismic risk areas). (121 pages)</td>
</tr>
<tr>
<td>PERU</td>
<td>Prescriptive guidelines for adobe structures, and some engineering guidelines addressed to areas of both moderate and high seismic risk. (21 pages)</td>
</tr>
</tbody>
</table>
Index to comparative review of documents by categories

1. Materials and systems
   1.1 Building systems covered / recognized
   1.2 Earthen material requirements
   1.3 Mortars
   1.4 Plasters and renders
   1.5 Reinforcing materials
   1.6 Material properties
   1.7 Testing and quality control

2. Prescriptive (“deemed to comply”) standards
   2.1 Limitations of application
   2.2 Minimum wall thickness and aspect ratio (wall height / wall thickness)
   2.3 Bond beams and diaphragms
   2.4 Bracing walls
   2.5 Restrictions on openings / lintels and headers
   2.6 Minimum reinforcing
   2.7 Roof overhangs and moisture protection
   2.8 Foundations
   2.9 Tolerances and quality control

3. Engineering design guidelines & standards
   3.1 Limits of application
   3.2 Allowable stresses
   3.3 Design for flexure & axial loads
   3.4 Design for lateral loads
   3.5 Special seismic loading considerations
Comparative review of documents by categories

1. Materials and systems— **1.1 Building systems covered / recognized**

   **ASTM**  
adobe, stabilized adobe, compressed block, rammed earth, cob, and poured earth  
*walls only (not vaults or domes) — typical of all documents*

   **ARIZ**  
adobe, “burnt adobe”, stabilized earth, compressed block, rammed earth, and  
puddled earth

   **AUST**  
adobe, stabilized adobe, compressed block, rammed earth, cob, and poured earth

   **CA**  
existing adobe only

   **IBC**  
adobe, stabilized adobe

   **IND**  
adobe, cob, rammed earth and *Assam* (wattle and daub) without any stabilizers

   **NEP**  
stone masonry only; up to two stories with cement mortar, one story with earth

   **NM**  
adobe, stabilized adobe, burned adobe, rammed earth, “Terrón” (dried cut sod)

   **NZ97**  
adobe, stabilized adobe, compressed block, rammed earth, and poured earth

   **NZ98**  
adobe, stabilized adobe, compressed block, rammed earth, poured earth;  
cob and earth  
floors discussed in “informative” (not part of standard) appendix

   **NZ99**  
adobe, stabilized adobe, compressed block, rammed earth; explicitly excludes cob,  
poured earth, and wattle and daub

   **PERU**  
adobe, stabilized adobe
Comparative review of documents by categories

1. Materials and systems— 1.2 Earthen material requirements

**ASTM** general description without specifics

**ARIZ** requires conformance to 1994 Uniform Building Code (UBC) Standard 71-1

**AUST** no requirements given; general and extensive description of desireable soils, stabilizers, admixtures, fibers, and suggested combinations; field tests for soil properties

**CA** (no comment)

**IBC** requires only that soil used for stabilized adobe be chemically compatible with stabilizer

**IND** “suitable soil” as defined by prescribed tests (see section 1.7)

**NEP** (no comment)

**NM** All: two percent limit on soluble salts, free of organic matter, “stabilizers” defined. Adobe: limits on warping or cracking; Rammed earth: maximum rock size 1.5”, maximum clay lump 0.5”; asphalt stabilization disallowed; Compressed earth: maximum rock size 1”

**NZ97** reference to NZ98

**NZ98** excludes mixes with over 15% by weight cement; defines “standard” and “special” (higher) grades of earth wall construction, with respective limitations and reference to NZ97 & NZ99; detailed limitations on particle size, soluble salts, admixtures, etc.

**NZ99** reference to NZ98

**PERU** 10–20% clay, 15–25% silt, 55–70% sand, no organic soils, may contain straw, no stones greater than 5 mm.
Comparative review of documents by categories

1. Materials and systems— 1.3 Mortars

**ASTM** (no comment)

**ARIZ** same as earth blocks, or type M or S mortar per 1994 UBC chapter 21

**AUST** no requirements given; general and extensive description of desirable mortar properties

**CA** (no comment)

**IBC** vaguely worded; requires portland cement mortar for unstabilized adobe

**IND** same mix as for adobes, amended as needed with straw and/or sand to reduce cracking

**NEP** cement-based mortar required for two story structures

**NM** same as earth blocks, or type M, N or S lime-cement mortar

**NZ97** reference to **NZ98**

**NZ98** detailed requirements (with commentary) given for mortars

**NZ99** reference to **NZ98**

**PERU** two types defined and allowed: soil with cement, lime, or asphalt stabilizer, or soil with straw to match bricks, minimum thicknesses given
Comparative review of documents by categories

1. **Materials and systems** — 1.4 *Plasters and renders*

<table>
<thead>
<tr>
<th>Code</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM</td>
<td>general description without specifics; allows cement plaster</td>
</tr>
<tr>
<td>ARIZ</td>
<td>required for unstabilized walls “equivalent to ¾ inch cement plaster”</td>
</tr>
<tr>
<td>AUST</td>
<td>no requirements given; general and extensive description of desirable render properties</td>
</tr>
<tr>
<td>CA</td>
<td>(no comment)</td>
</tr>
<tr>
<td>IBC</td>
<td>for unstabilized adobe, requires two-coat cement plaster per ANSI A42.2, and metal lath per ANSI A42.3 fastened to wall</td>
</tr>
<tr>
<td>IND</td>
<td>mud plaster recommended as part of water protection regimen; amendment with cow dung, bitumen, and/or kerosene described for high rain exposure conditions</td>
</tr>
<tr>
<td>NEP</td>
<td>(no comment)</td>
</tr>
<tr>
<td>NM</td>
<td>earth plaster allowed; cement plaster with metal mesh allowed with prescribed metal fasteners to wall and flashing as needed. “Approved” plaster required over unstabilized rammed earth.</td>
</tr>
<tr>
<td>NZ97</td>
<td>reference to NZ98</td>
</tr>
<tr>
<td>NZ98</td>
<td>preconstruction testing defined in appendix, with detailed description of required or desired properties, mixing, application and curing of plaster (render)</td>
</tr>
<tr>
<td>NZ99</td>
<td>reference to NZ98</td>
</tr>
<tr>
<td>PERU</td>
<td>sand-cement mortar with wire mesh tied through wall allowed</td>
</tr>
</tbody>
</table>
Comparative review of documents by categories

1. Materials and systems — **1.5 Reinforcing materials**

- **ASTM**
  - general description of straw (as component of adobe) without specifics

- **ARIZ**
  - not discussed, other than steel reinforcing for concrete bond beams

- **AUST**
  - reinforcing steel, barbed wire and wire mesh; wood, bamboo; fiber-reinforced plastic mesh and geotextile fabric; extensive discussion and illustration of reinforcing details

- **CA**
  - (no comment)

- **IBC**
  - (no comment)

- **IND**
  - steel (where concrete used); wood, cane and bamboo charred or painted with coal tar

- **NEP**
  - steel, bamboo or timber

- **NM**
  - steel reinforcing bars and steel attachments between earthen walls and other components such as wood lintels and top plates.

- **NZ97**
  - reinforcing requirements described for steel; parallels used where possible with concrete and masonry design

- **NZ98**
  - reinforcing requirements described for steel; commentary on use of geogrid, barbed wire, bamboo, fiberglass, kevlar, etc

- **NZ99**
  - reinforcing requirements described and illustrated in detail

- **PERU**
  - split cane, wooden strips in adobe, steel reinforcing in concrete collar beams and (where used) columns
Comparative review of documents by categories

1. Materials and systems—1.6 Material properties

**ASTM**  (no comment)

**ARIZ**  requires conformance to Uniform Building Code (UBC) Standard 71-1

**AUST**  review of typical properties historically measured, and provides in tabular form recommended minimum structural properties, for each of the various earth building systems;

**CA**  (no comment)

**IBC**  minimum 300 psi in compression, 50 psi MOR, less than 4% moisture content, no more than three shrinkage cracks, none over three inches long or 1/8 inch wide; limits water absorption of stabilized adobe to 2.5%

**IND**  1.2 N/mm² in compression for adobes; other properties defined by partly subjective tests

**NEP**  (no comment)

**NM**  limits shrinkage cracks, minimum compressive strength 300 psi and MOR of 50 psi for adobe; minimum tested compressive strength 300 psi for rammed earth and compressed earth blocks.

**NZ97**  reference to **NZ98**

**NZ98**  extensive description of material properties and test methods for establishing and/or verifying those properties.

**NZ99**  reference to **NZ98**

**PERU**  requires minimum compressive (2 kg/cm²) and shear (0.25 kg/cm²) strength of blocks
Comparative review of documents by categories

1. Materials and systems—

**1.7 Testing and quality control**

ASTM  general reference to tests (eg compressive strength, Modulus of Rupture, water absorption, and erosion) for similar materials

ARIZ  (no comment)

AUST  field tests described and illustrated; laboratory tests described

CA  subject to engineering judgement and historic experience

IBC  requires sample compression tests per ASTM C67, MOR sample tests by method described, and water absorbtion test for stabilized adobe by method described

IND  field tests for desired properties defined and illustrated

NEP  (no comment)

NM  requires sample compression tests for adobe and rammed earth, and MOR sample tests for adobe and compressed adobe

NZ97  reference to tests in appendices of NZ98

NZ98  requires and defines curing for cement and lime-stabilized earth; detailed requirements (with commentary) given for testing prior to and during construction; many tests carefully defined and illustrated in appendices

NZ99  reference to tests in appendices of NZ98

PERU  field tests for allowable stresses defined and illustrated
Comparative review of documents by categories

2. Prescriptive “deemed to comply” standards— **2.1 Limits of application**

**ASTM**  none given

**ARIZ**  maximum one story or 16 feet high unless engineered

**AUST**  primarily but not exclusively one and two story structures

**CA**  existing one and two story adobe structures

**IBC**  one story buildings, or two story if designed by licensed professional

**IND**  one and two story dwellings in low seismic risk zones; two story dwellings only in high seismic risk zones with explicit caveat that prescriptive standards “raise weather and seismic resistance greatly” but do not guarantee against collapse. No siting in loose, soft soils or areas of very high water table, especially in seismic risk zones

**NEP**  one and two story dwellings

**NM**  one and two story dwellings

**NZ97**  walls up to 6.5 meters high; excludes (but allows subject to specific testing and rational analysis) higher walls, arches, vaults and domes; retaining walls not included

**NZ98**  defines “standard” and “special” (higher) grades of earth wall construction, with respective limitations and reference to **NZ97 & NZ99**

**NZ99**  Extensive limits described for building plan size and height (varying with seismic risk zone), roof slope and framing, local wind speeds, rainfall and snow loads, and floor use and construction

**PERU**  one story in high seismic risk, two stories in lower risk zones, disallowed in sites with soft or expansive soils, or areas prone to flood, mudslide, or geological instability; roof must be “as light as possible”, distribute weight evenly, not exert lateral thrust on walls, and overhang walls with consideration for climactic conditions of the site
### Comparative review of documents by categories

2. **Prescriptive standards**

<table>
<thead>
<tr>
<th>Standard</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ASTM</strong></td>
<td>no comment</td>
</tr>
<tr>
<td><strong>ARIZ</strong></td>
<td>given in tabular format as function of dead &amp; wind loads, and seismic zone</td>
</tr>
<tr>
<td><strong>AUST</strong></td>
<td>describes minimum wall thickness and aspect ratio for the various earth building systems, with reductions for high-risk seismic areas</td>
</tr>
<tr>
<td><strong>CA</strong></td>
<td>h/t &lt; 6 for one story buildings and second level of two-story buildings; h/t &lt; 5 for first level of two-story buildings; requires check of tall partitions and gable end walls</td>
</tr>
<tr>
<td><strong>IBC</strong></td>
<td>minimum 10” (exterior walls), 8” (interior), and never h/t &gt; 10;</td>
</tr>
<tr>
<td><strong>IND</strong></td>
<td>h/t &lt; 8 in seismic risk areas</td>
</tr>
<tr>
<td><strong>NEP</strong></td>
<td>3.2 meter maximum wall height, nor more than 8x thickness</td>
</tr>
<tr>
<td><strong>NM</strong></td>
<td>wall thicknesses 10 to 24”, allowable heights given in table as function of seismic risk. Rammed earth exterior walls at least 18” thick, interior walls 12” thick.</td>
</tr>
<tr>
<td><strong>NZ97</strong></td>
<td>minimum wall thicknesses and slenderness ratios given as function of building system and seismic risk</td>
</tr>
<tr>
<td><strong>NZ98</strong></td>
<td>reference to criteria in <strong>NZ97 &amp; NZ99</strong></td>
</tr>
<tr>
<td><strong>NZ99</strong></td>
<td>minimum and maximum wall thicknesses and need for reinforcement given as function of building system and seismic risk</td>
</tr>
<tr>
<td><strong>PERU</strong></td>
<td>wall thicknesses from 0.3 to 0.5 M; bracing and reinforcing requirements given as function of aspect ratio</td>
</tr>
</tbody>
</table>
Comparative review of documents by categories

2. Prescriptive standards—2.3 Bond beams & diaphragms

ASTM no comment

ARIZ wood or concrete bond beam, or roof diaphragm, required. Bearing and bending capacity of concrete bond beams (of varying size & reinforcing) defined in tables.

AUST describes, illustrates concrete and timber bond beams and their function

CA requires reinforced concrete bond beam and anchorage

IBC bond beams of concrete or wood required and defined

IND requires good roof connection; wood bond and lintel beams required, defined, and detailed for high seismic risk areas

NEP wood or concrete bond beam or horizontal wall reinforcing required

NM “in accordance with accepted engineering practices”; wood or concrete sizes defined, minimum roof anchorage defined

NZ97 requires that wall tops be restrained

NZ98 bond beams of wood or concrete, and diaphragms, defined by reference to NZ97, NZ99, and other NZ standards

NZ99 bond beam and diaphragm requirements described and illustrated in extensive detail

PERU bracing at top of wall required by wood or concrete collar beam “of adequate stiffness” and designed for anchorage; lightweight roofs disallowed as structural diaphragms
Comparative review of documents by categories

2. Prescriptive standards—2.4 Bracing walls

ASTM  (no comment)

ARIZ  not specifically addressed (focus is on bracing tops of walls)

AUST  general recommendation for uniform distribution of walls in plan, and reference to New Zealand standards (NZ97, NZ98, and NZ99)

CA  (no comment)

IBC  24 foot maximum spacing of undefined “lateral support”, and isolated load-bearing piers (wall sections less than 24 inches long) disallowed

IND  in seismic risk area: recommends symmetry in plan, and limits wall length between bracing walls to be less than 10 times thickness t and less than $64t^2/h$ (illustrated)

NEP  5 meter maximum distance between bracing walls; “bracing wall” defined in table as function of braced wall thickness and height

NM  24 foot max spacing between bracing walls; “bracing” defined and connections to exterior wall illustrated.

NZ97  general comment about preference for symmetrical, uniform distribution of walls

NZ98  reference to criteria in NZ97 & NZ99

NZ99  “bracing walls” and bracing requirements described and illustrated in detail

PERU  maximum length of wall (between bracing walls) = 12 times thickness; bracing connection details given; “bracing wall” defined
Comparative review of documents by categories

2. Prescriptive standards

<table>
<thead>
<tr>
<th>Standard</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM</td>
<td>(no comment)</td>
</tr>
<tr>
<td>ARIZ</td>
<td>(no comment)</td>
</tr>
<tr>
<td>AUST</td>
<td>describes, illustrates and limits size, locations, and total area of openings for non-engineered buildings; describes and details many types of lintels</td>
</tr>
<tr>
<td>CA</td>
<td>(no comment)</td>
</tr>
<tr>
<td>IBC</td>
<td>no comment on size or number of openings; lintels to be designed per IBC chapter 16</td>
</tr>
<tr>
<td>IND</td>
<td>width of openings less than 1.2 m; proximity of openings to corners less than 1.2 m; and aggregate opening in wall limited to 33% and 40% in higher and highest seismic risk zones (illustrated). Minimum lintel bearing 300 mm.</td>
</tr>
<tr>
<td>NEP</td>
<td>“as small and centrally located as practicable”; illustration for guidance, lintel bearing at least 300 mm.</td>
</tr>
<tr>
<td>NM</td>
<td>wood or concrete lintel sizes given in tabular format as function of span &amp; load; spacing and proximity to corners of openings limited and detailed.</td>
</tr>
<tr>
<td>NZ97</td>
<td>(no specific comment)</td>
</tr>
<tr>
<td>NZ98</td>
<td>(no specific comment)</td>
</tr>
<tr>
<td>NZ99</td>
<td>lintel reinforcing requirements described and illustrated in detail</td>
</tr>
<tr>
<td>PERU</td>
<td>openings “small and preferably centered in wall”; details and elaboration as to best locations given as function of wall thickness and proximity to bracing</td>
</tr>
</tbody>
</table>
## Comparative review of documents by categories

2. Prescriptive standards— **2.6 Minimum reinforcing**

<table>
<thead>
<tr>
<th>Document</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM</td>
<td>(no comment)</td>
</tr>
<tr>
<td>ARIZ</td>
<td>structural calculations required when resisting in-plane forces</td>
</tr>
<tr>
<td>AUST</td>
<td>general requirements given for reinforcing size and layout</td>
</tr>
<tr>
<td>CA</td>
<td>(no comment)</td>
</tr>
<tr>
<td>IBC</td>
<td>(no comment)</td>
</tr>
<tr>
<td>IND</td>
<td>none given (see also section 3.5)</td>
</tr>
<tr>
<td>NEP</td>
<td>minimum steel given in schedule for cement mortared walls, bamboo or wood illustrated for other walls.</td>
</tr>
<tr>
<td>NM</td>
<td>(no comment)</td>
</tr>
<tr>
<td>NZ97</td>
<td>unreinforced structures allowed; extensive discussion and reinforcing guidelines largely derived from masonry and reinforced concrete requirements in other parts of the New Zealand Standards; caution against over-reinforcement against seismic loads</td>
</tr>
<tr>
<td>NZ98</td>
<td>spacing, tolerances and other minimum requirements for steel reinforcing or polypropylene geotextile grid given; reference to NZ97 and NZ99</td>
</tr>
<tr>
<td>NZ99</td>
<td>reinforcing requirements described and illustrated in extensive detail</td>
</tr>
<tr>
<td>PERU</td>
<td>prescriptive bracing and reinforcing requirements given as function of aspect ratio</td>
</tr>
</tbody>
</table>
Comparative review of documents by categories

2. Prescriptive standards— **2.7 Roof overhangs & moisture protection**

**ASTM**  
general discussion and description of durability strategies (stabilizers, plasters)

**ARIZ**  
protection required for unstabilized walls “equivalent to ¾ inch cement plaster”, disallows unstabilized earth near flor, roof parapets, and drains.

**AUST**  
describes, illustrates damp proofing, desirable plaster properties, overhangs, and other durability features; describes erosion tests; discusses and illustrates recommended eave overhangs based on wind conditions

**CA**  
(no comment)

**IBC**  
no comment about overhangs; “parapet walls of adobe shall be waterproofed”

**IND**  
500 mm minimum roof overhang

**NEP**  
(no comment)

**NM**  
llocations where moisture barriers required or disallowed defined; weather-resistive barrier over unstabilized rammed earth required.

**NZ97**  
discussion of appropriate plasters

**NZ98**  
(no comment)

**NZ99**  
minimum eaves given in table as function of rainfall, wind speeds, wall height, extensive requirements for wall durability; reference to **NZ98**

**PERU**  
requires protection from wetting and erosion by plasters, raised foundations, “perimetric sidewalks” [translation error?], overhanging roofs, and adequate drainage.
Comparative review of documents by categories

2. Prescriptive standards—2.8 Foundations

ASTM (no comment)

ARIZ extend at least six inches above ground, of same width as adobe; reference to other chapters covering foundations in general for depth, width, construction, etc.

AUST extensive discussion and illustration of soils, dimensions, drainage, reinforcing details; both prescriptive requirements and design guidelines provided

CA (no comment)

IBC extend at least six inches above ground, of solid (non-adobe) masonry or concrete; reference to chapter 18 covering foundations in general

IND dimensions and construction all defined and detailed for hard and soft soils

NEP width, bearing width, and construction all defined and detailed

NM extend at least six inches above ground, at least as thick as wall, except two inch inset allowed for edge insulation; reference to other chapters covering foundations in general for depth, width, construction, etc.

NZ97 extensive requirements described

NZ98 (no comment)

NZ99 extensive requirements described and illustrated

PERU requires concrete or masonry foundation, minimum dimensions described and illustrated for flat and sloped sites, minimum 20 cm above and 60 cm below grade
### Comparative review of documents by categories

2. **Prescriptive standards** — **2.9 Tolerances & quality control**

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM</td>
<td>general reference to tests for shrinkage and cracking limitations</td>
</tr>
<tr>
<td>ARIZ</td>
<td>(no comment)</td>
</tr>
<tr>
<td>AUST</td>
<td>describes, illustrates control joints and other shrinkage accommodation; dimensional tolerances defined similar to those for reinforced concrete</td>
</tr>
<tr>
<td>CA</td>
<td>(no comment)</td>
</tr>
<tr>
<td>IBC</td>
<td>(no comment)</td>
</tr>
<tr>
<td>IND</td>
<td>field tests for determining good building soil, and quality of finished adobe blocks (MOR test) described and illustrated</td>
</tr>
<tr>
<td>NEP</td>
<td>(no comment)</td>
</tr>
<tr>
<td>NM</td>
<td>general and detailed requirements for rammed earth formwork and workmanship</td>
</tr>
<tr>
<td>NZ97</td>
<td>requires control joints to account for shrinkage</td>
</tr>
<tr>
<td>NZ98</td>
<td>requires construction review; detailed requirements (with commentary) given for testing prior to and during construction; many tests carefully defined and illustrated in appendices; dimensional tolerances defined similar to those for reinforced concrete</td>
</tr>
<tr>
<td>NZ99</td>
<td>reference to NZ98</td>
</tr>
<tr>
<td>PERU</td>
<td>“free of cracks, alien materials, and other defects that may diminish resistance [strength?] or durability”; mortar and reinforcing details given</td>
</tr>
</tbody>
</table>
Comparative review of documents by categories

3. Engineering design guidelines & standards— 3.1 Limits of application

ASTM none given

ARIZ maximum one story or 16 feet high unless engineered

AUST primarily, but not exclusively, for single- or two-storey earth wall construction

CA existing adobe structures

IBC one story buildings, or two story if designed by licensed professional

IND at most two stories high, further restrictions on “Important Buildings” in high seismic risk zones, disallowed on sites with soft soils or very high water table

NEP one and two story dwellings of stone masonry

NM one and two story dwellings of any of the earthen wall systems covered

NZ97 walls up to 6.5 meters high; excludes (but allows subject to specific testing and rational analysis) higher walls, arches, vaults and domes; retaining walls not included

NZ98 reference to NZ97 and NZ99

NZ99 extensive restrictions on height, floor area, roof overhangs, live loads and materials given as functions of seismicity, rainfall, wind speeds, soil bearing capacity, and snow loads

PERU adobe, stabilized adobe
Comparative review of documents by categories

3. Engineering design guidelines & standards— **3.2 Allowable stresses**

**ASTM**
general reference to ANSI/ASCE-7 design loads for strength or working stress design

**ARIZ**
30 psi allowable compression, 4 psi allowable shear, 0 psi allowable tension (working stress method; adjustments given in table). Allowable bolt shear given in table.

**AUST**
review of typical properties historically measured, and provides in tabular form recommended minimum structural properties, for each of the various earth building systems;

**CA**
4 psi allowable shear stress

**IBC**
30 psi allowable compressive stress; allowable shear on bolts in adobe given in table

**IND**
(no comment)

**NEP**
(no comment)

**NM**
(no comment)

**NZ97**
extensive discussion and presentation of allowable structural stresses, bolt loads in earth, as well as fire resistive properties and thermal properties; reference to **NZ98**

**NZ98**
preconstruction testing defined in appendices, with statistical methods for deriving allowable stresses (or acceptance of material)

**NZ99**
(no comment other than reference to **NZ98**)

**PERU**
unit compressive strength 12 kg/cm², masonry (wall) compressive strength 0.2 $f_m$, or 2 kg/cm², bearing strength 1.25 $f_m$, masonry shear strength 0.25 kg/cm², all subject to defined field tests
Comparative review of documents by categories

3. Engineering design guidelines & standards—

**3.3 Flexure & axial loads**

**ASTM**  general reference to ANSI/ASCE-7 design loads for strength or working stress design

**ARIZ**  general reference to 1994 UBC

**AUST**  extensive discussion and guidelines largely derived from masonry and reinforced concrete procedures

**CA**  (no comment)

**IBC**  (no comment)

**IND**  (no comment)

**NEP**  (no comment)

**NM**  no comments beyond material strength requirements

**NZ97**  extensive discussion and guidelines largely derived from masonry and reinforced concrete requirements in other parts of the New Zealand Standards

**NZ98**  (no comment)

**NZ99**  prescriptive requirements given for wall construction and layout

**PERU**  prescriptive bracing and reinforcing requirements given as function of aspect ratio
Comparative review of documents by categories

3. Engineering design guidelines & standards— 3.4 Design for lateral loads

**ASTM**
- general reference to ANSI/ASCE-7 design loads for strength or working stress design

**ARIZ**
- general reference to 1994 UBC

**AUST**
- extensive discussion and guidelines largely derived from masonry and reinforced concrete procedures

**CA**
- (no comment)

**IBC**
- (no comment)

**IND**
- (no comment)

**NEP**
- (no comment)

**NM**
- no comments beyond material strength requirements

**NZ97**
- extensive discussion and guidelines largely derived from masonry and reinforced concrete requirements in other parts of the New Zealand Standards

**NZ98**
- (no comment)

**NZ99**
- prescriptive requirements given for wall construction and layout

**PERU**
- design by rational method based on elastic behavior; design force defined as a function of site soils, building usage, seismic risk zone, and dead + 50% of live load.
Comparative review of documents by categories

3. Engineering design guidelines & standards— **3.5 Seismic load considerations**

**ASTM**  general requirement to give consideration

**ARIZ**  general reference to 1994 UBC

**AUST** describe and limits openings, wall aspect ratio, building plan proportions, roof construction, acceptable foundation soils, etc. for non-engineered buildings; explicitly does not address engineered seismic design

**CA**  (no comment)

**IBC**  (no comment)

**IND**  many recommendations given throughout for high risk areas, and additional bracing details defined and detailed in appendix

**NEP**  (no comment)

**NM**  no comments beyond material strength requirements, and wall aspect ratios as a function of area seismicity

**NZ97**  extensive special requirements given for seismic loading; detailed and illustrated appendix suggests methodology for axial plus out-of-plane loading on unreinforced walls

**NZ98**  (no comment)

**NZ99**  extensive special requirements given for wall construction, detailing, reinforcing and layout

**PERU** design by rational method based on elastic behavior; design force defined as a function of site soils, building usage, seismic risk zone, and dead + 50% of live load.
Conclusions

Specific

There is far more commonality than disagreement among these documents, but a few items bear mentioning:

1) **Cement-stabilized earth**, or soil-cement, is essentially weak concrete (though one year compressive strengths of over 6,000 psi have been measured for rammed earth—hardly “weak”). Put another way, “concrete” is just a specialized type of soil-cement that by definition has as little fines (silt and clay) as practicable. Almost all the standards recognize, discuss, and generally encourage cement stabilization of earth. Yet alone among them all, the IBC implicitly recognizes the possibility of alkali-silica reaction (ASR), and sulphate attack—both highly deleterious chemical reactions between certain well-known soil types and cement, and both well known in the concrete industry. The IBC deftly accounts for this possibility by simply requiring that any additive to the soil be chemically compatible with the earthen components. This leaves it entirely up to the designer/builder, as is the case with concrete, to test mixtures so as to establish compatibility.

2) **Cement plasters** of one inch or greater thickness are, by North American definitions, “vapor barriers” (ie they show resistance to the passage of water vapor of one or less U.S. Perms). As such, they should generally not be used on earthen walls, especially unstabilized ones. Yet many of the reviewed standards allow or even require cement plasters over earth walls, presumably on the undying belief that this will ensure or enhance durability. It is now widely known that this is not the case, and that in fact a nice thick cement plaster can and will damage or destroy the underlying wall by trapping moisture—typically in the form of condensed vapor “trying to escape”. It is somewhat less known, but well established, that the inclusion of hydrated lime in the plaster will radically increase vapor permeability. This is just one of the reasons why lime is included in most pre-mixed stucco plasters in the USA, another being that it adds workability. Typical US codes allow up to one part lime to one part cement for exterior plasters, though even one part lime to four parts cement will increase permeability to three or more US Perms.

3) **Engineering analysis** of both unreinforced and reinforced earth walls has to date drawn heavily on established methods for reinforced concrete and concrete masonry. As many have already noted, however, the similarities are limited: earthen material strength and bond strength with rebar can vary widely, even within a single project, and fundamental engineering assumptions such as stress being proportional to strain, or that plane sections remain plane, are suspect. Put differently, this is to say that earthen structures under load, especially seismic load, quickly leave their elastic range and behave plastically. Recognizing this, many are now talking about both retrofit and new construction design being based on stability analysis. Seismic design in general could be said to be moving away from controlling stresses in any particular part of the building, and thinking more holistically about the entire structure and simply preventing collapse in extreme seismic events. Much of the testing to date on earthen structures, as well as observations of extant buildings affected by recent earthquakes, has given us a much more refined sense of how the buildings react to seismic load, and how they tend to fail. Thus we have an increasingly good sense of where to concentrate reinforcing (be it steel rebar, bamboo strips, wire or plastic mesh, burlap, etc.), and to one degree or another each of the reviewed documents reflect this growing knowledge.
General

Our engineering understanding of earthen construction has come along dramatically in the past two decades. There is of course still much more to learn—every answered question generates three new unanswered ones—but that is the case with all building materials, and with scientific testing in general. We are still learning a lot about concrete, steel, and wood-panel shearwalls (just to pick three examples), but that is not cause not to use those materials in building structures. Likewise, we are reasonably well-equipped at present to define a reliable standard of practice for earthen buildings, and indeed in many ways already have.

Even a cursory review of existing codes and standards for earthen construction reveals a striking range of styles, detail, clarity, and intent. Many of the documents are only a few pages of prescriptive requirements, yet have little else in common besides their brevity. Most standards in the United States, for example, often do not reflect a thorough understanding of earthen building, and are quite conservative, reflective of the trivial status earth building holds in this country. Other documents of similar size, such as the Peruvian Standard, were developed by people who have spent decades studying, testing, and improving earthen building systems; their standards are short and simple presumably because they recognize that anything more complex would or could not be enforced, and thus would have little effect on actual life safety in their country.

On another extreme, the trilogy of New Zealand Standards, along with the quasi-standard Australian Earth Building Handbook, dwarf all others in their sheer size and detail. Prescriptive standards in these documents for wall dimensions, for example, will fill eight or ten pages with requirements, commentary, and graphic illustration, where by contrast the corresponding section of the Indian Standard consists of a few very short paragraphs and one illustration. This disparity is not necessarily reflective of a different level of knowledge, understanding, or intent to safeguard the public. Rather, it illustrates the inescapable underlying fact of writing codes and standards: *Any written document, including a scientific or engineering one, is inevitably reflective both of the mindset of its author(s), and of the audience to whom it is addressed.*

To pretend or act otherwise can lead to unwanted, unintended or terrible results. If, for example, the New Zealand Standards were by some fiat adopted in Mali, Nicaragua, or rural China, they would likely be summarily ignored, or, worse, lead to the razing, or disqualifying from insurance, financing, or simple governmental acceptance, of most of the regional housing stock while offering no viable means of replacement to the occupants. At best—with the standards ignored—they would have had no positive effect.

This is by no means intended as a criticism of the New Zealand Standards (or the Australian Earth Building Handbook, or any of the other standards). The New Zealand Standards in particular are well-organized, thorough, clearly-illustrated, and—alone among the documents reviewed—provide commentary interspersed with requirements that greatly assist the readers’ understanding and interpretation. Nonetheless, they are addressed to an affluent audience, not to the tens of millions of people worldwide who live in earthen structures because they have no choice.

The trick, indeed the very large trick, is to develop standards while recognizing that the vast majority of users for those standards are among the poorest people in the world. This dilemma is unique to those who study and work with earthen construction; virtually all engineers in the USA, for example, never consider whether or not their clients can afford a ton of rebar, 20 bags of cement, or a few rafters for a roof. As engineering understanding of structures and material properties has advanced over the decades, so have the resulting codes and standards become more exacting in what they require of a builder. Only very recently has anyone begun to question the socioeconomic and environmental ramifications of the evolution of codes and standards.

How, then, do we as engineers write standards for durability and life safety that lead to structures that are both affordable and safe? If we write standards that no one uses because they can’t, then what have we done to safeguard the public?
Precedents and alternatives to the
“highest possible level of life safety, sparing no expense”
philosophy of building codes and standards

Here are three examples that suggest routes to new and, for lack of a better word, flexible standards:

**California Historical Building Code** (sections 8-701-2 and 8-706.1)
“It is the intent of these regulations to encourage the preservation of qualified historical buildings while providing a reasonable level of structural safety for occupants and the public at large . . . . It is the intent of these regulations to provide for the use of historical methods and materials of construction that are at variance with regular code requirements or are not otherwise codified . . . . the forces used to evaluate the structure for resistance to wind and seismic loads need not exceed 0.75 times the seismic forces prescribed by the 1995 edition of the California Building Code.”

The implicit philosophy in this language is that we can and even should relax life safety standards somewhat so as not to disturb the architectural or cultural qualities of designated structures. Whether or not one agrees with this societal choice, the precedent is there, and has been for some time.

**Indian Standard** (section 1.2, note 2)
“Attention is hereby drawn to the fact that earthen construction as dealt with herein will neither qualify as engineered construction nor totally free from collapse in severe seismic intensities (VIII and IX on the MM scale). However, inclusion of special design and construction features as recommended in this standard will raise their weather and seismic resistance appreciably reducing greatly the chances of collapse even in such seismic intensities.” [sic]

Here the philosophy is to provide some guidelines that are relatively understandable and affordable, but don’t make any guarantees about life safety. (Indeed, as every engineer knows, no standards or codes do, but to the general public they appear that way). This is a refreshing candid way of offering guidelines to improve but not guarantee safety.

**Mendocino County, California** (“Class K Limited Density Rural Dwelling Permit”)
“Class K is a relaxed construction standard available to owner-built rural dwellings and appurtenant structures intended ‘...to allow and facilitate the use of alternatives to the specifications prescribed by the Uniform technical codes to the extent that a reasonable degree of health and safety is provided...’ To qualify, the property must be zoned for a one acre minimum, and the class K status of the structure must be disclosed upon any subsequent sale.”

Here the code bows to the mythic and entrenched American attitude of “It’s my land and I can do what I damn-well want!” by saying, in effect, “Fine, do so. But if you ever sell the land, you have to disclose that what you built was not necessarily consistent with the building codes”, and leaves the owner with the flexibly-interpreted requirement of “keeping to a reasonable degree of health and safety”.

Of the three approaches presented, the last two suggest reasonable solutions to the need for affordable standards. Neither, however, address engineering language, requirements or analysis. Rather, they require a new or modified approach to governance, to society’s choice as to how much rule can or should be forced on the individual, even for life safety. Even so, the job still falls to we engineers who work with earthen construction to help people, as best we can, to make do with what is at hand, with what they can acquire. Much progress on that front has been made, and much still awaits our attention.
Supplements  (additional documents reviewed for this paper)

2005 [Morocco]  International Workshop on Building Codes for Traditional Materials

Achenza, Maddalena 2005 [Italy]
 A National Law for Earthen Architecture in Italy / Difficulties and Expectations

Bariola, Juan 2005 [Peru]
 Seismic Analysis of Adobe Structures

Blondet, Marcial, Vargas, Julio and Tarque, Nicola 2005 [Peru]
 Building Codes for Earthen Buildings in Seismic Areas

Blondet, Marcial, Torrealva, Daniel, Villa Garcia, Gladys, Ginocchio, Francisco and Madueño, Ivonne 2005 [Peru]
 Using Industrial Materials for the Construction of Safe Adobe Houses in Seismic Areas

Huynh, Thanh-Hue, Meyer, Patrick, and Ostertag, Claudia 2005 [USA]
 Burlap Reinforcement for Improved Toughness of Low-Cost Adobe Residential Structures

Iyer, Sreemathi, and Schierle, G.G. 2005 [India]
 Bamboo Masonry Reinforcement for Earthquake Resistance

Morris, Hugh 2005 [New Zealand]
 Seismic Research on Earth Building related to the 1998 New Zealand Earth Building Standards


Tolles, E.L. 2004 [USA]
 Overview of the Getty Adobe Research of the 1990’s

Walker, Peter 2003 [UK]
 Review of Structural Design Procedures for Earth Buildings

Webster, Fred 2005 [USA]
 Application of Stability-Based Retrofit Measures on Some Historic and Older Adobe Buildings in California

Webster, Fred 1995 [USA]
 Some Thoughts on Adobe Codes
Conversions

**Force and Pressure**

1 kilogram per square centimeter (kg/cm²) = 14.22 pound/square inch (psi)
1 newton/square millimeter = 1 pascal (Pa) = 145.04 pound/square inch (psi)
1 kilopascal (kPa) = 0.145 pound/square inch (psi)
1 kilonewton (kN) = 224.81 pounds (lbs)

**Length and Distance**

1 centimeter (cm) = 0.393 inch (in)
1 meter (m) = 3.281 feet (ft) = 39.37 inches (in)

**Velocity**

1 meter/second (m/s) = 2.24 mile/hour (mph)

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mixing mud

Wagga Wagga, Australia, 2003
photo courtesy of Graeme North