11 Mar 1998, 1:30 pm - 4:00 pm

Morphoseismic Features in the New Madrid Seismic Zone (central USA) and their Implications for Geotechnical Engineering

Ray Knox
Bella Vista, Arkansas

David Stewart
Marble Hill, Missouri

Proceedings: Fourth International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri, March 9–12, 1998.

MORPHOSEISMIC FEATURES IN THE NEW MADRID SEISMIC ZONE (CENTRAL USA) AND THEIR IMPLICATIONS FOR GEOTECHNICAL ENGINEERING

Ray Knox
2 Lambourn Drive
Bella Vista, Arkansas-USA-72714

David Stewart
Route 1, Box 646
Marble Hill, Missouri-USA-63764

Paper No. 3.22

ABSTRACT

Morphoseismic features are new landforms produced by earthquakes or pre-existing landforms modified by them. The New Madrid Seismic Zone (NMSZ) contains thousands of earthquake-related surface features distributed over 13,000 square kilometers. They are attributable to some combination of (1) seismically-induced liquefaction, (2) secondary deformation, and (3) seismically-induced slope failures. Most were produced by the series of great earthquakes that occurred in 1811-12, but some predate and some postdate those events. They are being modified by ongoing activities such a fluvial processes, mass wasting, eolian processes, hydrologically-induced liquefaction (HIL), mechanically-induced liquefaction (MIL), and human activities.

Dynamic responses to ground motion include sand extrusion, sand intrusion, lateral spreading, faulting, subsidence, uplift, stream modification, landsliding, groundwater flooding, and explosion cratering. We have identified thirty-four types of morphoseismic features. While the formation of these features during and following earthquakes can be devastating to engineering structures in place at the time of the ground motion, they pose unique hazards to structures built over them for all subsequent time. Geotechnical engineers working in the NMSZ, or any other region where large earthquakes occur, need to recognize and compensate for them.

KEYWORDS

New Madrid Seismic Zone, Morphoseismic features, Soil Liquefaction, Secondary Deformation, Slope Failures

INTRODUCTION

The New Madrid Seismic Zone (NMSZ) of southeastern Missouri, northeastern Arkansas, extreme western portions of Tennessee and Kentucky, and possibly a part of southern Illinois (Fig. 1), contains a large variety of landforms genetically related to earthquakes.

We suggest that the adjective "morphoseismic" be applied to landforms that have seismic origins or that have been significantly modified by seismic events. The noun form, "morphoseismology", would be defined as the study of these landforms. We recognize nine subcategories and 34 species in the NMSZ (Fig. 2).

Virtually all landforms in the NMSZ that existed in 1811 were modified to some degree by the series of great earthquakes that occurred in the winter of 1811-12. All landforms in the NMSZ, however, have also been modified since 1812 by erosion, sedimentation, differential compaction, and farming practices.

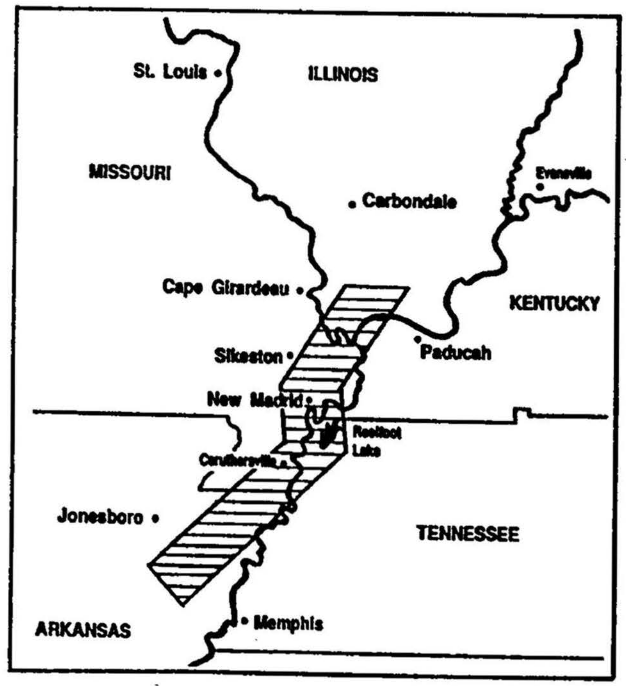

Fig. 1 New Madrid Seismic Zone.

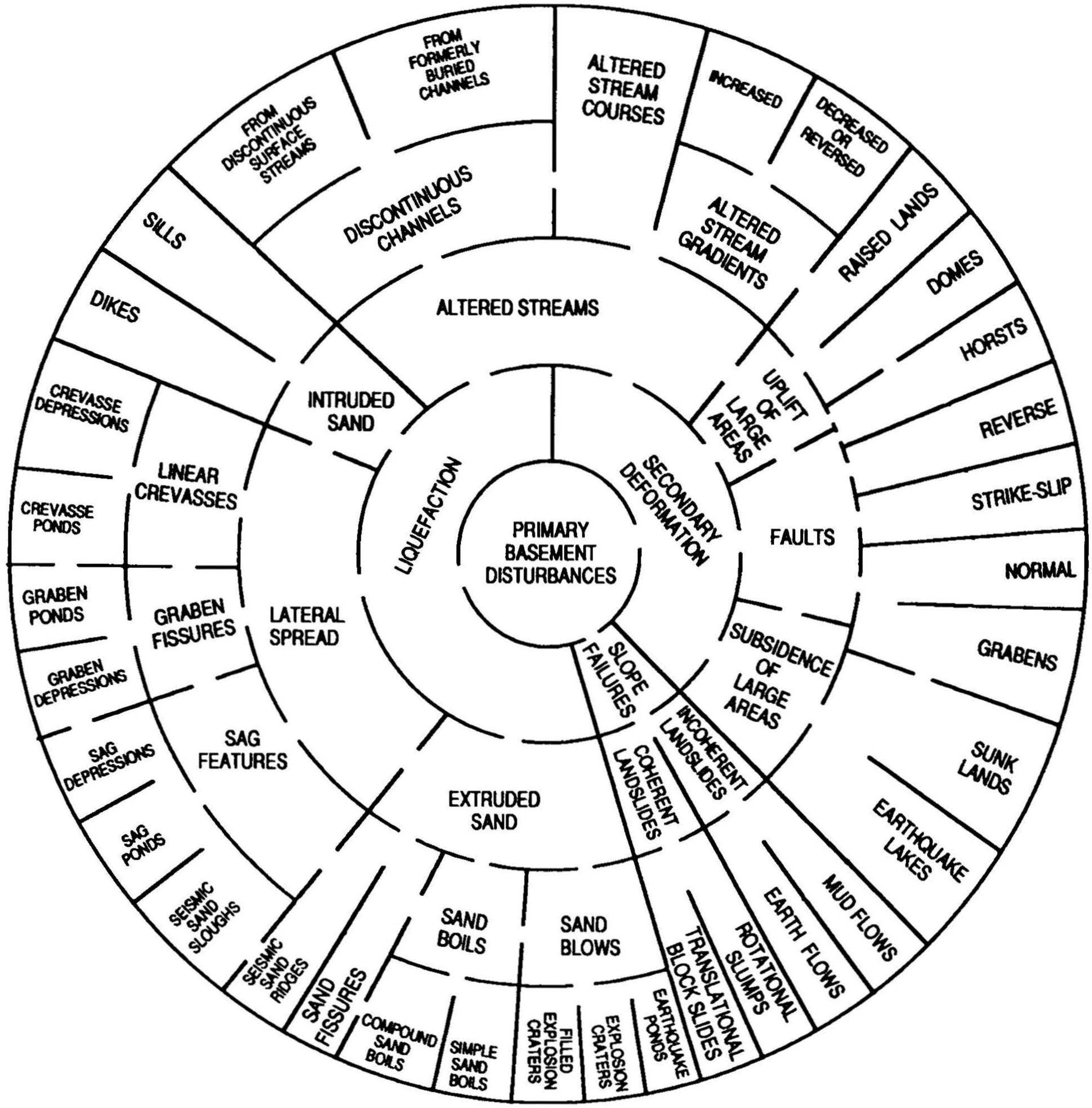

Fig. 2 Classification of morphoseismic features - dynamic model.

CLASSIFICATION OF MORPHOSEISMIC FEATURES

Figure 2 represents a classification device that illustrates the genetic origins and evolutions of these features, but at the same time emphasizes those that are seen in the NMSZ today. Time flows from the center outward, with the sequence of events leading to landforms seen today illustrated by the compartments in the two outer rings. The many "doors" in the maze represents an attempt to show that in many cases, more than one feature may result from the same combination of origins. For example, linear crevasses may become crevasse depressions or crevasse ponds, depending on the depth to the water table.

A parallel objective is to emphasize that the presence of the thousands of morphoseismic landforms, though mostly originating in 1811-12, still very much effect today's activities. Engineers dealing with bridges, highways, railroads, airports, overpasses, building construction, waste disposal, powerlines, pipelines, water runoff, flood control, and land development are among those who must work up their designs with a knowledge of the locations and characteristics of these features. Farmers, land use planners, and city, county, and state authorities need to recognize morphoseismic features in order to successfully mitigate and remediate their effects.

Few, if any, morphoseismic features are produced by one process. This is apparently true for even the broadest of categories. Primary basement disturbances generate body and surface waves that cause secondary deformation, liquefaction, and slope failures. Each of these terms represent entire families of processes and features that grade into others.

FEATURES RESULTING PRIMARILY FROM SOIL LIQUEFACTION

Soil liquefaction is the most important cause of morphoseismic features in the NMSZ (Fuller, 1912; Obermeier, 1988). The classic papers dealing with the subject are found in engineering journals (e.g., Seed, 1968; Seed and Idriss, 1982). The

TABLE 1: CLASSIFICATION OF MORPHOSEISMIC FEATURES - TRADITIONAL FORM

I. Features Related to Liquefaction

A. Extruded Sand Features
- 1. Sand Blows
  - a. Explosion Craters
  - b. Filled Explosion Craters
  - c. Earthquake Ponds
- 2. Sand Boils
  - a. Simple Sand Boils
  - b. Compound Sand Boils
- 3. Sand Fissures
- 4. Seismic Sand Ridges

B. Intruded Sand Features
- 1. Sand Dikes
- 2. Sand Sills

C. Lateral Spread Features
- 1. Sag Features
  - a. Sag Depressions
  - b. Sag Ponds
  - c. Seismic Sand Sloughs
- 2. Linear Crevasses
  - a. Crevasse Depressions
  - b. Crevasse Ponds
- 3. Graben Fissures
  - a. Graben Depressions
  - b. Graben Ponds

II. Features Related to Secondary Deformation

A. Faults
- 1. Strike Slip
- 2. Normal
- 3. Reverse
- 4. Grabens
- 5. Horsts

B. Subsidence of Large Areas
- 1. Sunk Lands
- 2. Earthquake Lakes

C. Uplift of Large Areas
- 1. Raised Lands
- 2. Domes

D. Altered Streams
- 1. Altered Stream Gradients
  - a. Reduced or Reversed Gradients
  - b. Increased Gradients
- 2. Altered Stream Courses
- 3. Discontinuous Channels
  - a. Discontinuous Surface Streams
  - b. Formerly Buried Stream Channels

III. Features Related to Slope Failures

A. Coherent Landslides
- 1. Translational Block Slides
- 2. Rotational Slumps

B. Incoherent Landslides
- 1. Earth Flows
- 2. Mud Flows

TABLE 2: LOCATIONS OF SELECTED EXAMPLES OF MORPHOSEISMIC FEATURES IN THE NEW MADRID SEISMIC ZONE

FEATURE	TOPO MAP AND LOCATION	COMMENTS AND INTERPRETATION
Filled Explosion Crater	Sikeston South, MO lat. 36.788 long. 89.532 NW, NE, NW, SEC 27 25N 14E	Two craters, 30m and 25m diam. Extruded through braided bar island Filled by farming practices
Filled Explosion Crater	Kewanee, MO lat. 36.684 long. 89.539 SE, NE, NE, SEC 33 24N 14E West side I-55 at mile 53 Just inside fence	Filled with soil Defies farming attempts Holds water in spring Hydrophytic plants even in August
Filled Explosion Crater	New Madrid, MO lat. 36.583 long. 89.546 NW, NW, NE, SEC 4 23N 14E 30m NW of church on north side of Kingshighway	Filled with bricks, concrete blocks, roofing material, appliances, general debris; used as dump for years
Earthquake Pond	Point Pleasant, MO lat. 36.440 long. 89.572 NE, NE, NE, SEC 30 21N 14E	50m by 200m dimensions. Only 150m from Mississippi river levee
Simple Sand Boil typical, modified	New Madrid, MO lat. 36.596 long. 81.524 NW, SEC 33 23N 14E	Typical field of nine or ten boils modified by agriculture and land development
Simple Sand Boil typical, modified	Luxora, AR lat. 35.785 long. 89.993 NE, NE, NW, SEC 2 13N 10E West side I-55. Other boils and fissures on east side	Classic sand boil. Extruded matter includes carbonized wood and petroliferous nodules
Simple Sand Boil rare, little	Kewanee, MO lat. 36.675 long. 89.550 NW, SE, SW, SEC 33 24N 14E	Mounded sand boil contained "witness tree" until 1996
Compound Sand Boil	New Madrid, MO lat. 36.569 long. 89.590 SW, NW, NW, SEC 7 22N 14E	Developed on natural levee of pre-1811 drainage Gut Ste. Ann Bayou.
Compound Sand Boil	New Madrid, MO lat. 36.582 long. 89.554 NW, NW, NW, SEC 4 22N 14E	"Sinclair Sand Boil" area 3 ha
Sand Fissures	Portageville, MO lat. 36.4 long. 89.7 W half SEC 6 20N 13E	Scores of sand fissures in fields on both sides of highway "T"
Seismic Sand Ridge Seismic Sand Slough	Kewanee lat. 36.661 lat. 36.661 long. 89.531 NE, SE, SW, SEC 3 23N 14E	Two seismic sand ridges flanking seismic sand slough Field road south of LaForge
Sand Dikes Sand Sills	Steele, MO lat. 36.047 long. 89.800 NW, SE, SW, SEC 6 16N 12E	Clean off east bank of Franklin Ditch with shovels and trowels for best viewing
Sag Depression	New Madrid, MO lat. 36.581 long. 89.553 SE, NW, NW, SEC 4 22N 14E	South of levee which is good vantage point

continued . . .

TABLE 2: LOCATIONS OF SELECTED EXAMPLES OF MORPHOSEISMIC FEATURES IN THE NEW MADRID SEISMIC ZONE cont'd

Seismic Sag Pond	Portageville, MO lat. 36.425 long. 89.742 SW, SE, SE, SEC 27 21N 12E	70m north of Portage Open Bay Probable lateral spread sag Possible channel explosion or graben fissure
Crevasse Depression	Steele, MO lat. 36.069 long. 89.820 SE, SW, NW, SEC 36 17N 11E	Feature is 700m long, holds water intermittently
Crevasse Pond	Caruthersville, MO lat. 36.176 long. 89.658 NW, NE, NW, SEC 28 18N 13E	Probably lateral spread sag that intersects the water table
Graben Depression Graben Pond	Stanley, MO lat. 36.303 long. 89.694 W half SEC 7 19N 13E	Possible channel explosion feature ponded where depression intersects water table
Strike Slip Fault	From near Blytheville, AR to near New Madrid, MO	Bootheel Lineament Schweig and Marple, 1991
Normal Fault	Tiptonville, TN West side Reelfoot Lake	Reelfoot Fault Zoback, 1979
Reverse Fault		No known example that intersects surface
Graben		No known example that intersects surface
Horst	Tiptonville, TN; Point Pleasant, MO; New Madrid, MO; Hubbard Lake, MO	Central part of Tiptonville Dome Stewart and Knox, 1993
Sunk Land	Several well documented	Fuller, 1912
Earthquake Lake	Several well documented	Fuller, 1912
Raised Land	Several well documented	Fuller, 1912
Dome	700 km^2 centered around neck of New Madrid Bend lat. 36.5 long. 89.5	Tiptonville Dome Russ, 1979
Stream Gradient Reduced	Portageville, MO; Point Pleasant, MO lat. 36.43 to 36.47 long. 89.55 to 89.67 21N, 13,14E	Bayou Portage connected river traffic between the Mississippi and Little rivers prior to 1811-12 Stewart and Knox, 1995
Stream Gradient Reversed	Tiptonville, TN; Hubbard Lake, MO lat. 36.46 to 36.58 long. 89.45 to 89.38	Mississippi River retrograde motion between Islands 10 and 8 February 7, 1812 Penick, 1981
Stream Gradient Increased	New Madrid, MO lat. 36.57 to 36.51 long. 89.50 to 89.55	Mississippi River current accelerated from 1 km upstream from New Madrid to at least Island 11 Stewart and Knox, 1993

continued . . .

TABLE 2: LOCATIONS OF SELECTED EXAMPLES OF MORPHOSEISMIC FEATURES IN THE NEW MADRID SEISMIC ZONE cont'd

Stream Course Altered	New Madrid, MO lat. 36.58 long. 89.60 to lat. 36.57 long. 89.58 SEC 36 23N 13E	Gut Ste. Anne Bayou channel in part raised and deflected in part; lowered and flooded in part Fuller, 1912
Discontinuous Surface Stream	Kewanee and New Madrid, MO lat. 36.63 long. 89.60 to lat. 36.58 long. 89.55 SEC 13 23N 13E to SEC 4 22N 14E	Des Cyprie segmented by differential subsidence and channel explosions Stewart and Knox, 1993
Formerly Buried Channel	Steele, MO lat. 36.12 long. 89.85 SE SW SEC 10 17N 11E	Former channel of Pemiscot Bayou liquefied, exploded, and differentially subsided Knox and Stewart, 1995
Slope Failures	Scores well documented	Jibson and Keefer, 1988
Photos of NMSZ morphoseismic features	More than one hundred	Stewart and Knox, 1993
Road Logs to NMSZ morphoseismic features	Hundreds of features	Knox and Stewart, 1995
Distant Sand Boils 251 km (157 mi) n/o New Madrid	St. Louis County Columbia Bottoms Florissant, MO	Stewart and Knox, 1995a. *The Earthquake Am Forgot*, GR Publications, p. 192
Distant Sand Boils 239 km (149 mi) n/o New Madrid	St. Louis County n/o I-70 & SE of MO River Bridge Earth City, MO	Stewart and Knox, 1995a *The Earthquake Am Forgot*, GR Publications, p. 192

END OF TABLE 2

probability of liquefaction is high if the sediment consists of sand or silt, is fully saturated, is poorly consolidated, and if the ground surface is level. The probability of liquefaction decreases with increasing clay ratios, although clays with sand/silt lenses are susceptible to liquefaction. The probability of liquefaction increases with the magnitude of cyclic stresses and the number of stress cycles. High confining pressures require some combination of greater cyclic stresses and/or greater duration of ground motion to induce liquefaction.

The duration of the ground motion is one of the most important of the variables. One control of the duration is simply distance from the epicenter. As a rule of thumb, within the meizoseismal zone, duration of significant ground motion doubles about every 100 km from the epicenter.

Extruded sand features

This category constitutes what appears to be an entire spectrum - ranging from those caused by the most violent (e.g. sand blows) to those caused by the most gentle ejections (e.g. sand boils).

All extruded sand features pose problems for engineers.. Many examples can be cited where highways (e.g. Knox and Stewart, 1995, p.87;97), railroads (e.g. Stewart and Knox, 1993, p. 65), or even farm equipment (e.g. Stewart and Knox, 1993, p.142;157) has gotten "bogged down" by mechanically- induced liquefaction of these features. Evidence is plentiful that many of these landforms have been supplied with liquefied sand through more than one episode. The point to remember is that extruded sand features will liquefy much more readily than surrounding soil, whether the cause is seismic, hydrologic, or mechanical.

Sand blow explosion craters. These are circular conical depressions 5-75 meters in diameter and 0.5-2 meters deep. At the time of formation, many of these were on the order of 5-7 meters deep (Fuller, 1912). Stream channels seem to have been especially susceptible to violent ejections of air, sand, and presumably, water. Another factor may be the nature of the sediment above the liquefied zone. More sand blows are found (compared to sand boils) where the overlying material is dry sand rather than where it contains a higher ratio of clay soil. Few of these features remain because of natural sedimentation processes and filling by humans - especially for agricultural purposes. Many have been used as dumps, by native Americans who seem to have considered them in siting their villages, and then by European-Americans to the present day (Stewart and Knox, 1993, p. 64, 127).

Filled explosion craters. These are usually at or slightly lower than the elevation of the surrounding land. When filled by natural processes, the sediment generally grades in size from coarse at the bottom to fine at the top (Gohn et al, 1984). The material at the surface is usually dark-colored, organic-rich, and damp or covered with a few centimeters of water. Often, various growths of hydrophytic plants are seen as "circular green spots" in fields that are otherwise cultivated for crops. Farmers avoid these patches because they lack the strength to support a tractor, or even a person on foot in some cases. They should also be avoided in siting most engineering projects.

Earthquake ponds. These are sand blow explosion craters that intersect the water table. Because they were not dug by humans, they have no spoil banks or dams. They are not recharged by surface runoff, but by ground water from beneath. The water levels in these ponds rise and fall with fluctuations of the water table.

Simple sand boils. These are extruded from a single vent, are circular to elliptical, sometimes elongated, and range widely in diameter from as little as one meter to well over 100 meters. The sand boils visible today are probably the larger ones, generally four meters or more in diameter. Most sand boils are slightly mounded or convex, but few are more than a meter high. Sand features higher than one meter are almost always sand dunes, erosional remnants of terraces, or portions of old natural levees. Although usually composed of sand, medium to fine gravel can sometimes be found. Lignite fragments and splinters of carbonized wood are often found. Some of these are coated with sulfur compounds or limonite, and a few boils actually contain small limonite particles. Some of the dark organic particles have a bituminous or petroliferous odor and burn readily in a hot flame.

The soils comprising sand boils become wet and dry more quickly than surrounding soils. They respond differently to compaction and to seismic ground motion than surrounding soils.

Compound sand boils. The characteristics of simple sand boils also apply to compound sand boils, except for the shape, size, and number of vents. Most simple sand boils are circular or elliptical. The greater the elongation and the more irregular the shape, the more likely that the feature is a compound sand boil formed by the coalescence of sand from two or more vents, or by multiple ejections through time (Vaughn, 1991), or both. Compound sand boils can grow to huge dimensions as more and more nearby simple boils merge into a single compound boil, or as more and more episodes of seismic ground motion create new ejections of added sand. Future NMSZ earthquakes will certainly reactivate essentially the same areas (Saucier, 1989: Nuttli, 1990; Stewart, 1991) Several compound sand boils in the NMSZ are four hectares or more in area.

Sand fissures. These may be linear or curvilinear and are simply crevasses that opened deeply enough to allow liquefied sand below to gush upwards, filling them with sand. Sand fissures are usually at or near grade and can be more than 1 km long. The widths range from a few centimeters to more than 10 meters. Sand fissures have many of the same liquefaction-prone sensitivities as sand boils, and, like boils, fragments of carbonized wood and lignite can often be found. Farmers avoid sand fissures during wet seasons, because vibrations from machines tend to create mechanically-induced liquefaction, causing them to "bog down".

Seismic sand ridges. When a linear crevasse opens deeply enough, it can be filled with liquefied sand from below, forming a sand fissure. If the liquefied sand continues to flow after the crevasse is filled, then it flows out on both sides forming a seismic sand ridge. Seismic sand ridges can be several kilometers long and as much as a 1.5 km wide, though most are much smaller. They are usually linear and often found parallel to other ridges with intervening sags or sloughs.

Intruded Sand Features.

By definition, intruded features are normally not exposed at the surface. Drainage canals or borrow pits sometimes cut through them. Trenches dug by researchers working in the NMSZ have exposed several more (e.g., Schweig, 1991). Intruded sand features are included here because they have a common genesis with extruded sand features.

Sand dikes and sand sills. Sand dikes, or sand-filled crevasses, rarely reach the surface and are usually vertical or nearly so, and discordant with the layers of sediment into which they are intruded. Many have been supply vents for past extruded sand features, and are awaiting reactivation in future earthquakes (Russ, 1979). Sand sills are lenses of sand which are forced between and concordant with layers of sediment.

Lateral spread features.

When liquefied sand moves beneath non-liquefied layers of soil and sediment, associated changes in volumes and bearing capacities may cause the ground surface to sag, break open as crevasses, or drop down as one or more coherent blocks. Horizontal displacements can total many meters and leave large open cracks at the surface. Lengths of 200 meters or more are not unusual.

Lateral spread is most likely to occur on gentle slopes, but can form on horizontal, low-lying alluvium adjacent to a failing stream bank (Fuller, 1912). Apparently, the slope of the liquefiable zone or seam is a more important control than the slope of the surface. Test borings to identify potential liquefiable zones or seams thus become even more critical.

Sag features. Lateral spread sags are produced when liquefied sand moves, resulting in volume loss and a "sag" or subsidence of the land surface in a noncoherent manner. Sags are simply the low places in "wrinkled" terrain caused by differential subsidence during and after volume shifts of underlying liquefied sand. Where sags are deep enough to intersect the water table, Sag Ponds are formed. Where sags intersecting the water table parallel seismic sand ridges, presumably because the underlying liquefiable sand moved laterally and upward to produce the ridges, Seismic sand sloughs (pronounced "sloos") result.

Linear crevasses. These form when laterally-spreading, liquefied sand causes the non-liquefied layers above to break open. The opened crack through the more brittle, non-liquefied layer above is usually linear or curvilinear. As seen today, most linear crevasses are relatively narrow, from a few centimeters to a few meters wide, and have narrow bottoms. For those that intersect the water table the term crevasse ponds apply, otherwise the term crevasse depression is more appropriate. Linear crevasses are often found parallel to nearby stream channels, indicating that the flow of liquefied sediment was in the direction of the stream channel. Stream valleys apparently "invite" lateral spreading because the stream banks are unsupported slopes. Linear crevasses contain no ejected sand, but usually contain materials deposited since formation.

Graben fissures. These landforms represent the next level of lateral spreading. Instead of a sag or crevasse, a down-dropped block moves as a coherent unit, replacing liquefied material. Graben fissures can extend from only a few meters in length to more than a kilometer. The widths range from 2 or 3 to 50 meters. They contain little or no extruded sand. Those intersecting the water table are called graben ponds, otherwise the term graben depressions is more appropriate. The depths of graben fissures average between 0.5 and 5 meters. Another characteristic is the "canoe" shape. They usually pinch out on both ends, having no natural surface outlet.

FEATURES RELATED TO SECONDARY DEFORMATION

This category includes a family of morphoseismic surface features that primarily result from movements along basement fault blocks and the cascade of events generated by these movements (Braile, et al.,1984; Gomberg, 1991). In areas on the surface above actively rising or subsiding basement fault blocks, upwarping and downwarping of the entire sedimentary sequence may occur, directly affecting the land surface (Buschbach and Schwalb, 1984). In zones near contacts between active fault blocks and loose, saturated sandy sediment, sudden shifts may create deep liquefaction (Stewart and Knox, 1995), causing mobilization of saturated sediment from areas of greater to areas of lesser stress.

Subsidence of large areas. Sunk lands are depressions, covering large areas, that formed during the New Madrid (or earlier) earthquakes. They usually drain well enough not to become permanent lakes, but they may act as catchment basins for surface water runoff and become intermittent lakes. Fuller (1912) discussed sunk lands at length and shows the locations of many such areas on his regional map published in 1905 and included with his 1912 publication as a pocket insert. These features were sometimes several kilometers in extent and of many shapes, including linear, elliptical, and irregular. Earthquake lakes are actually sunk lands that are deep enough to intersect the water table. They hold water perennially, and differ from other low areas, such as lateral spread sags or sand sloughs that hold water intermittently. Earthquake lakes differ from earthquake ponds in that the latter result from explosive expulsion of sand during intense liquefaction. The most famous earthquake lake, Reelfoot Lake, covered 26,000 ha in 1812, but has "silted in" to only 5700 ha of open water (Fuller, 1912).

Uplift of large areas. Land areas are warped upward and downward during big earthquakes. Several contemporary accounts describe the occurrence of raised lands that were higher after the earthquakes than before. One of the most conspicuous of the uplifts is the Tiptonville Dome, (also called the Lake County Uplift), south of New Madrid Bend. This structure influences a surface area of some 650 square kilometers. The Tiptonville Dome has been repeatedly pushed upward, probably responding to numerous episodes of faulting (Zoback, 1979).

Faults. The primary New Madrid Fault severs Precambrian crystalline basement rocks five to 20 kilometers below the surface (Johnson, 1982). It is overlain by thousands of meters of Paleozoic, Mesozoic, and Cenozoic rocks and sediment. Thousands of small secondary faults were probably produced by the big earthquakes. Natural erosion processes and human modifications have eliminated most traces of fault scarps on the surface. Evidence from cleared walls of drainage canals and from backhoe trenching, however, show that many secondary faults do intersect the surface (e.g., Russ, 1979).

The Bootheel Lineament may be the longest of the faults that displace the Quaternary sequence. This feature can clearly be seen on satellite imagery (Schweig and Marple, 1991). It is 120 or 130 km long, and stretches from near Marked Tree, Arkansas to near New Madrid. Marked by massive SIL sand features, it is currently under study by researchers.

The most impressive of the landforms created by faulting in the NMSZ is undoubtedly the scarp of the Reelfoot Fault. This fault, located just west of Reelfoot Lake, separates the raised land to the west, the Tiptonville Dome, from the sunk land to the east, now including Reelfoot Lake. The prominent escarpment, up to 10 m high, has been trenched and described by Russ (1979).

Altered streams. Streams are susceptible to all forms of soft-sediment deformation. Perhaps the most publicized set of stream alterations were the notorious "waterfalls" that appeared during the greatest of the historic New Madrid earthquakes, on February 7, 1812, and lasted for a few days. It is best not to visualize these features as great plunging waterfalls. A better image is one that resembles the "falls of the Ohio" River, which drops some 8 m over a distance of three km (Penick, 1981). Renewed movements on faults that strike across the bed of the Mississippi River almost certainly created the cascades. The "falls" lasted for only a few days, before the river was able to reestablish its former gradient by wearing away these deformities.

Less dramatic, but far more common varieties of altered streams are the discontinuous channels. These landforms usually meander and "pinch out" on both ends. Most of them are rarely more than 3 m deep or 4-5 m wide. At first, many appear to simply be remnants of old drainages modified by farmers. On closer inspection, however, it becomes apparent that most do not have a consistent gradient as does an unmodified surface drainage channel. Many gather water from two or more directions.

FEATURES RESULTING FROM SLOPE FAILURES

The Upper Mississippi Embayment is flanked on the west, north, and east by escarpments which face New Madrid. Landslides exist on most, if not all these escarpments, and evidence suggests that many, perhaps most of the larger ones were triggered by the great series of earthquakes that occurred during the winter of 1811-12 (Fuller, 1912; Jibson and Keefer, 1988). Smaller escarpments are found at the flanks of some of the larger stream terraces. Many of these slopes have failed also.

Most of the larger documented slope failures in the NMSZ are found along the bluffs east of the Mississippi River from Memphis, Tennessee to Wickliffe, Kentucky. Jibson and Keefer (1988) identified more than 200 landslide features which they attribute to earthquake shaking.

Several landslides can be identified with quite-recent, relatively small earthquakes. Thompson and Stewart (1992) documented, in considerable chronological detail, a landslide in the Benton, Missouri area which was triggered by the September 1990 (body wave magnitude 4.7) New Hamburg earthquake. At least two other small slope failures within a few km of the epicenter are attributed to the same earthquake. Even smaller earthquakes may, under "favorable" conditions, trigger small landslides (Keefer, 1984; Lemos and Coelho, 1991). It seems reasonably certain that scores of small landslides in the Benton and Bloomfield Hills await mapping.

A statement sometimes attributed to landslides is that "once a landslide - always a landslide". Old landslides will always be the first to slide or flow again with future ground motion. Many old slide areas are so unstable that even non-seismic events may set them in motion.

SUMMARY AND CONCLUSIONS

The New Madrid Seismic Zone contains an array of features that were created by the 1811-12 series of great earthquakes and a continuum of previously existing landforms that were modified to various degrees by these earthquakes. Morphoseismic features are related to each other, to pre-existing nonseismic landforms, to the duration and intensity of ground motion, and to factors such as soil and sediment properties and the water table. Future earthquakes will reactivate many of these. Geotechnical engineers need to identify and understand them. Ongoing research will continue to add to and modify our efforts, hopefully leading to a more clear understanding of the effects of earthquakes on the landscape, and successful mitigation of the effects of future ones.

REFERENCES

Braile, L.W. et al. [1984]. "Tectonic development of the New Madrid Seismic Zone." in *"Proc. Symp. on New Madrid Seismic Zone."* U.S. Geol. Surv. Open File Report 84-770, pp. 204-233.

Buschbach, T.C., and H.R. Schwalb. [1984]. "Sedimentary geology of the New Madrid Seismic Zone." in *"Proc. Symp. on the New Madrid Seismic Zone"*. U.S. Geol. Surv. Open File Rept. 84-770, pp. 64-96.

Fuller, M., [1912]. *"The New Madrid earthquake."* U.S.G.S. Bull. 494. Avail. from Gutenberg-Richter, Marble Hill, MO.

Gohn, G.S. et al. [1984]. "Field studies of earthquake-induced liquefaction-flowage features in the Charleston, South Carolina, area--preliminary report." U.S. Geol. Surv. Open File Rept. 84-670.

Gomberg, J., [1991]. (abs.) "Tectonic deformation in the New Madrid Seismic Zone." Seis. Res. Ltrs., v. 62.

Jibson, R.W., and D.K. Keefer. [1988]. "Landslides triggered by earthquakes in the central Mississippi Valley, Tennessee and Kentucky." U.S. Geol. Surv. Prof. Paper 1336-C.

Johnson, A.C., [1982]. "A major earthquake zone on the Mississippi." Sci. Am. v. 246, n.4.

Keefer, D.K. [1984]. "Landslides caused by earthquakes." Geol. Soc. Am. Bull. v. 95, pp. 406-421.

Knox, B.R. and D. Stewart, [1995]. *"The New Madrid Fault Finders Guide."* Gutenberg-Richter Publications, Marble Hill, MO.

Lemos, L., and P. Coelho. [1991]. "Displacements of slopes under earthquake loading." Proc. Second Inter. Conf. On Recent Adv. In Geo. Engrg. And Soil Dyn., St. Louis, MO.

Nuttli, O.W. [1990]. *"Effects of earthquakes in the central United States."* Avail. from Gutenberg-Richter, Marble Hill, MO.

Obermeier, S.F. [1988]. "Liquefaction potential in the central Mississippi Valley." U.S. Geol. Surv. Bull. 1832.

Penick, J. [1981]. *"The New Madrid earthquakes."* U. MO. Press.

Russ, D.P. [1979]. "Late Holocene faulting and earthquake recurrence in the Reelfoot Lake area, northwestern Tennessee." Geol. Surv. Am. Bull., v. 90, pp. 1013-1018.

Saucier, R. [1989]. "Evidence for episodic sand-blow activity during the 1811-12 New Madrid (Missouri) earthquake series." Geology, v.17, pp. 103-106.

Schweig, E.S. [1991]. (abs.) "The bootheel lineament: results of trenching and shallow seismic reflection studies." Seis. Res. Letters, v. 62.

Schweig, E.S., and R.T. Marple [1991]. "Bootheel Lineament: A possible coseismic fault of the great New Madrid earthquakes." Geology, v.19, pp. 1025-1028.

Seed, H.B. [1968]. "Landslides during earthquakes due to soil liquefaction." Am. Soc. Civ. Eng; Journ. Soil Mech. And Found. Div., v.94.

Seed, H.B., and I.M. Idriss. [1982]. "Ground motions and soil liquefaction during earthquakes." Earthquake Engrg. Res. Inst; Mon. Series: Earthquake Mon. on Earthquake criteria, struct. design, and strong motion records; Berkelely, CA.

Stewart, D. [1991]. *"Damages and Losses from future New Madrid earthquakes."* Mo. State Emergency Man. Agcy., Jefferson City.

Stewart, D., and B.R. Knox. [1993]. *"The earthquake that never went away."* Gutenberg-Richter Publications, Marble Hill, MO.

Stewart, D., and B.R. Knox. [1995]. "What is the maximum depth liquefaction can occur?" in Proc. Third Intern. Conf. on Recent Adv. in Geo. Erthq. Engrg. And Soil Dyn., St. Louis.

Thompson, J.R., and D. Stewart. [1992]. "Landslides induced by a 4.7 magnitude earthquake in the Benton Hills of Missouri." Trans. Of Mo. Acad. Sci, v. 26, pp. 91-104.

Zoback, M.D. [1979]. "Recurrent faulting in the vicinity of Reelfoot Lake, northwestern Tennessee." Geol. Soc. Am. Bull., v. 90, pp. 1019-1024.