US 20180209106A1

(19) **United States**

(12) **Patent Application Publication**

Bartlett

(10) **Pub. No.: US 2018/0209106 A1**

(43) **Pub. Date: Jul. 26, 2018**

(54) **LIGHT-WEIGHT BRIDGE SUPPORT SYSTEMS AND METHODS OF USE**

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(21) Appl. No.: **15/744,453**

(22) PCT Filed: **Aug. 5, 2016**

(86) PCT No.: **PCT/US2016/045918**

§ 371 (c)(1),
(2) Date: **Jan. 12, 2018**

Related U.S. Application Data

(60) Provisional application No. 62/282,665, filed on Aug. 6, 2015, provisional application No. 62/253,439, filed on Nov. 10, 2015.

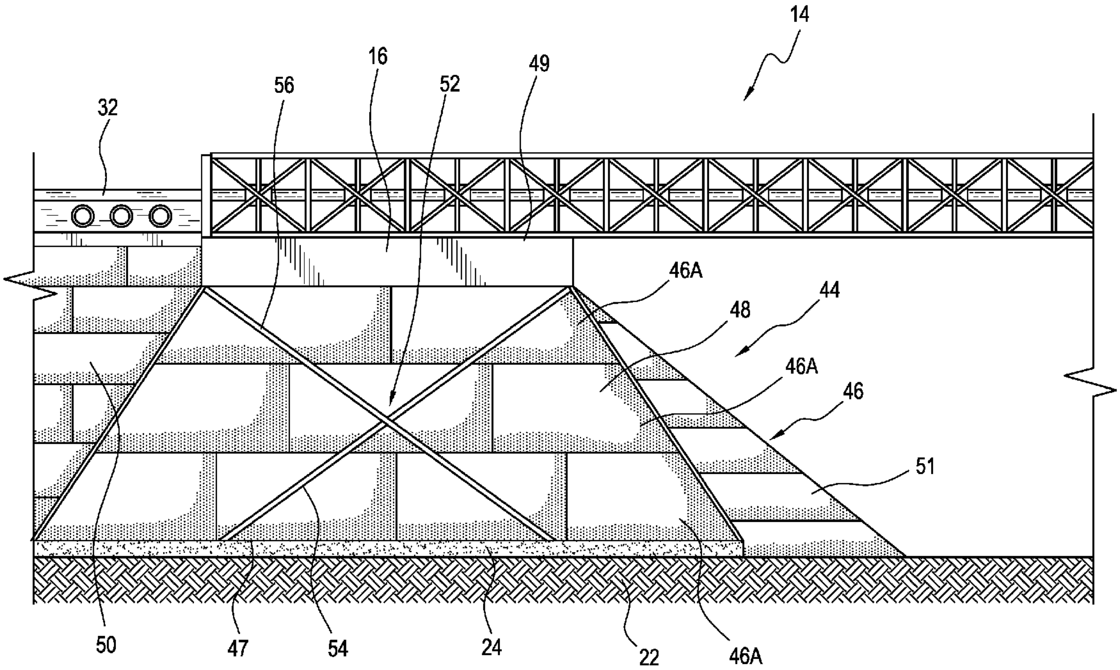
Publication Classification

(51) **Int. Cl.**
E01D 19/02 (2006.01)
E02D 17/18 (2006.01)

(52) **U.S. Cl.**
CPC ***E01D 19/02*** (2013.01); *E01D 2101/20* (2013.01); ***E02D 17/18*** (2013.01)

(57) **ABSTRACT**

A bridge support system includes a support embankment formed from at least one light-weight material. The support embankment is arranged to support and be positioned under a footing of a bridge structure. A restraining system is operatively connected to the support embankment. The restraining system includes cross-members which are angularly offset from each other and arranged to limit at least one of lateral and vertical movement of the support embankment under high levels of excitation.



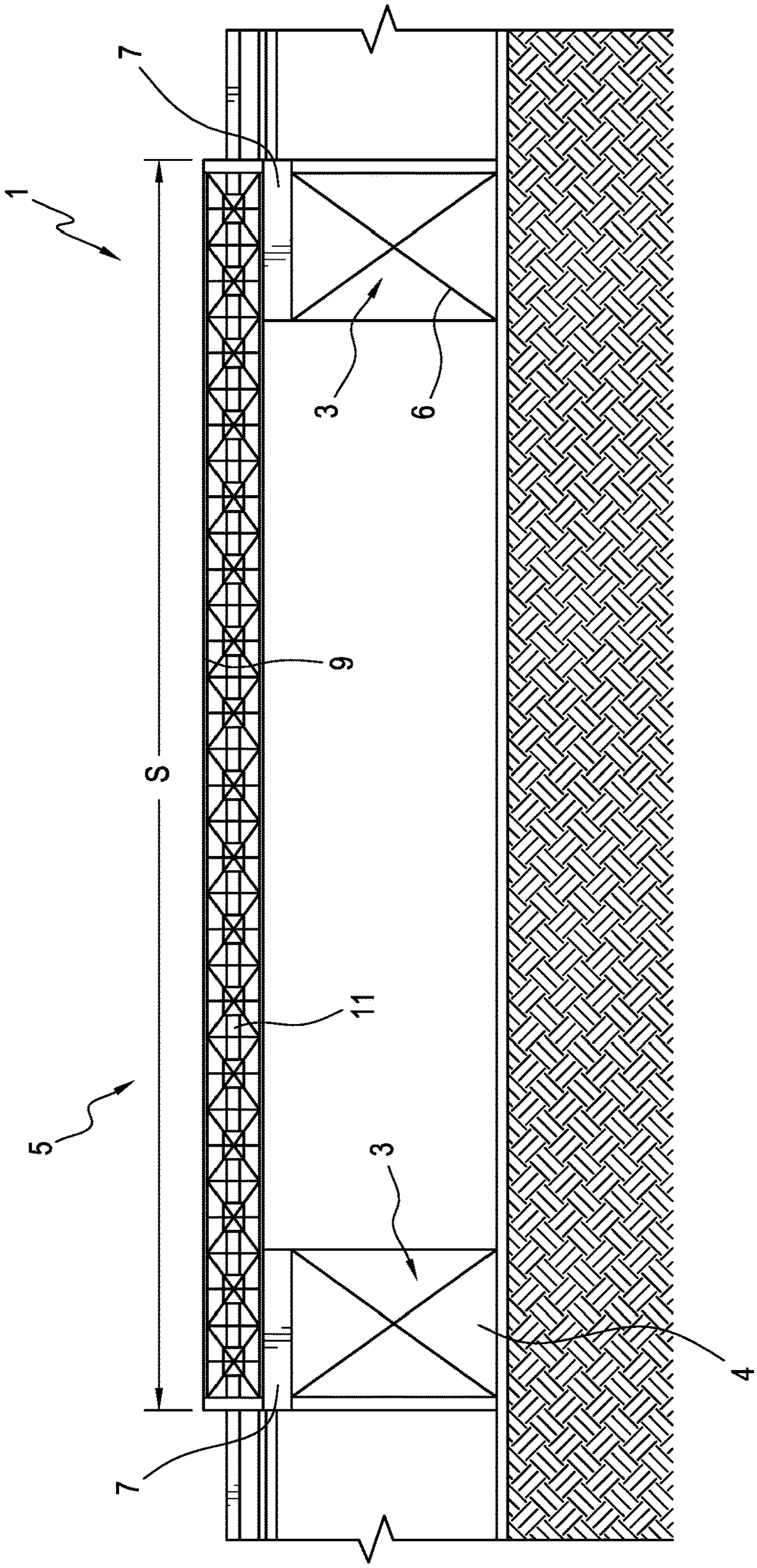


FIG. 1

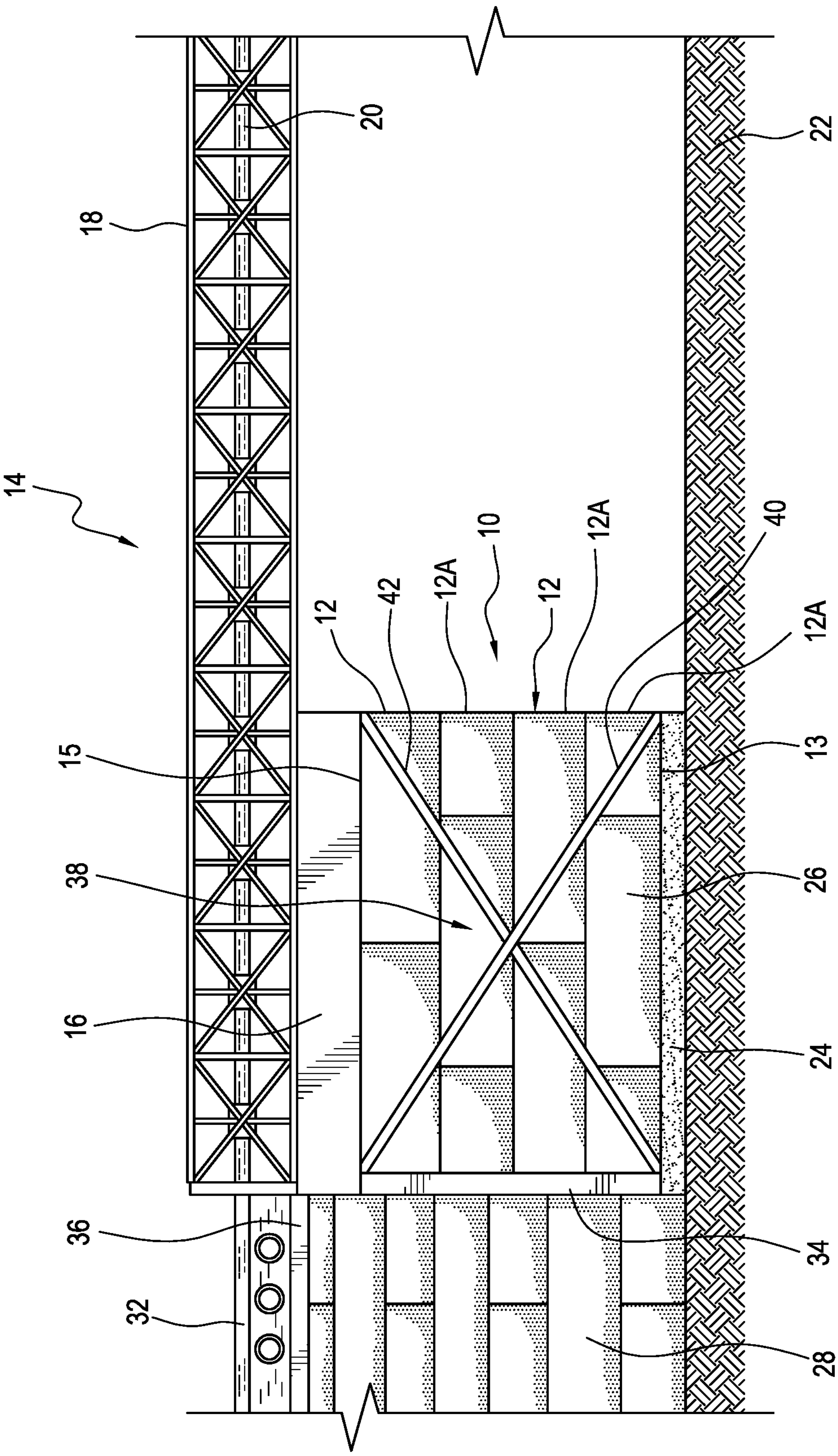


FIG. 2

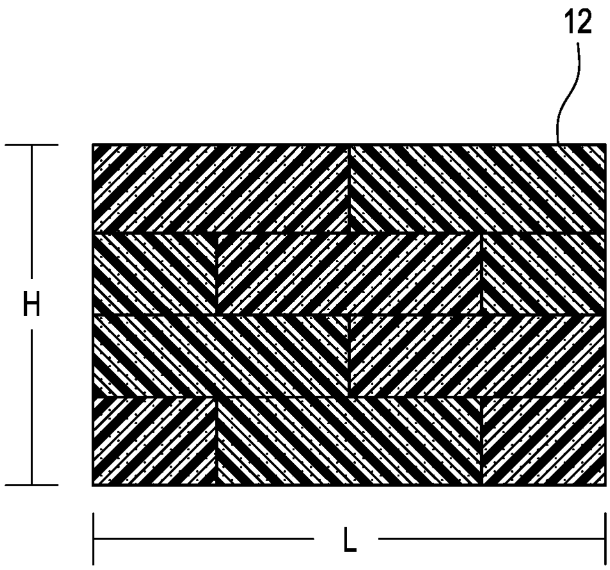


FIG. 3

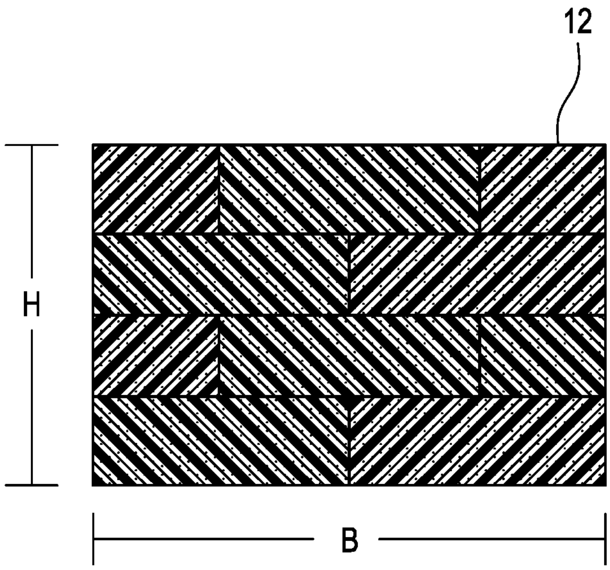


FIG. 4

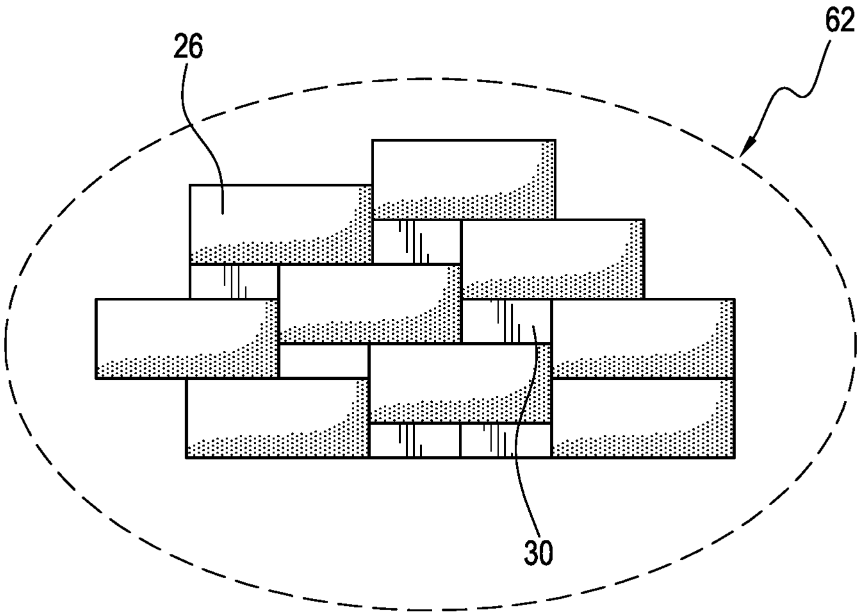


FIG. 5

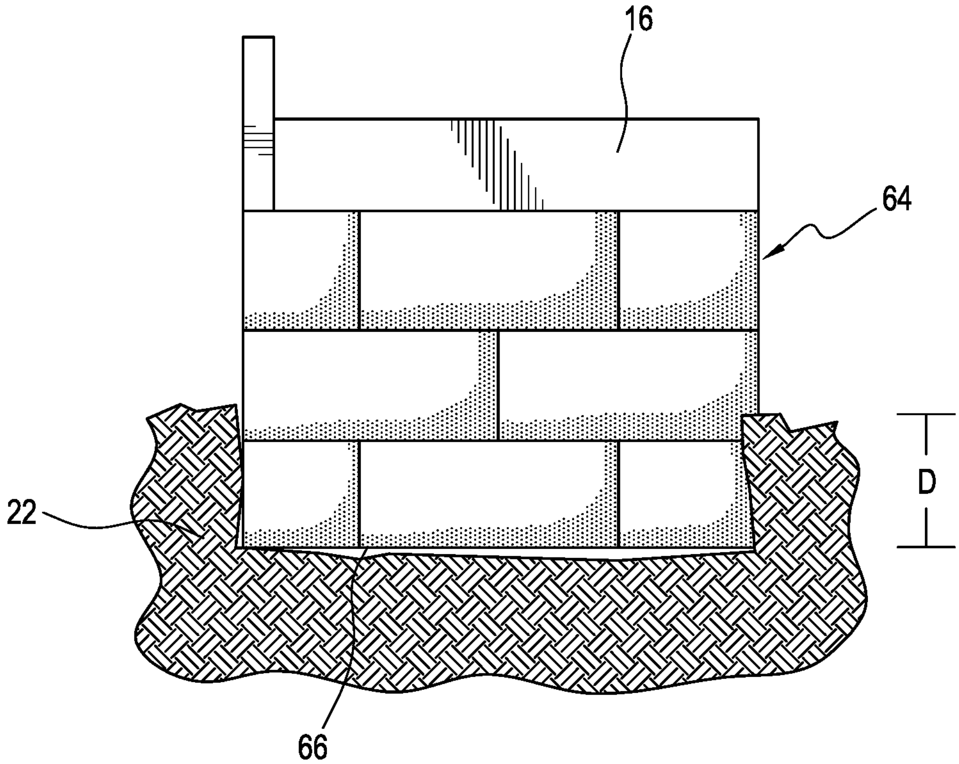


FIG. 6

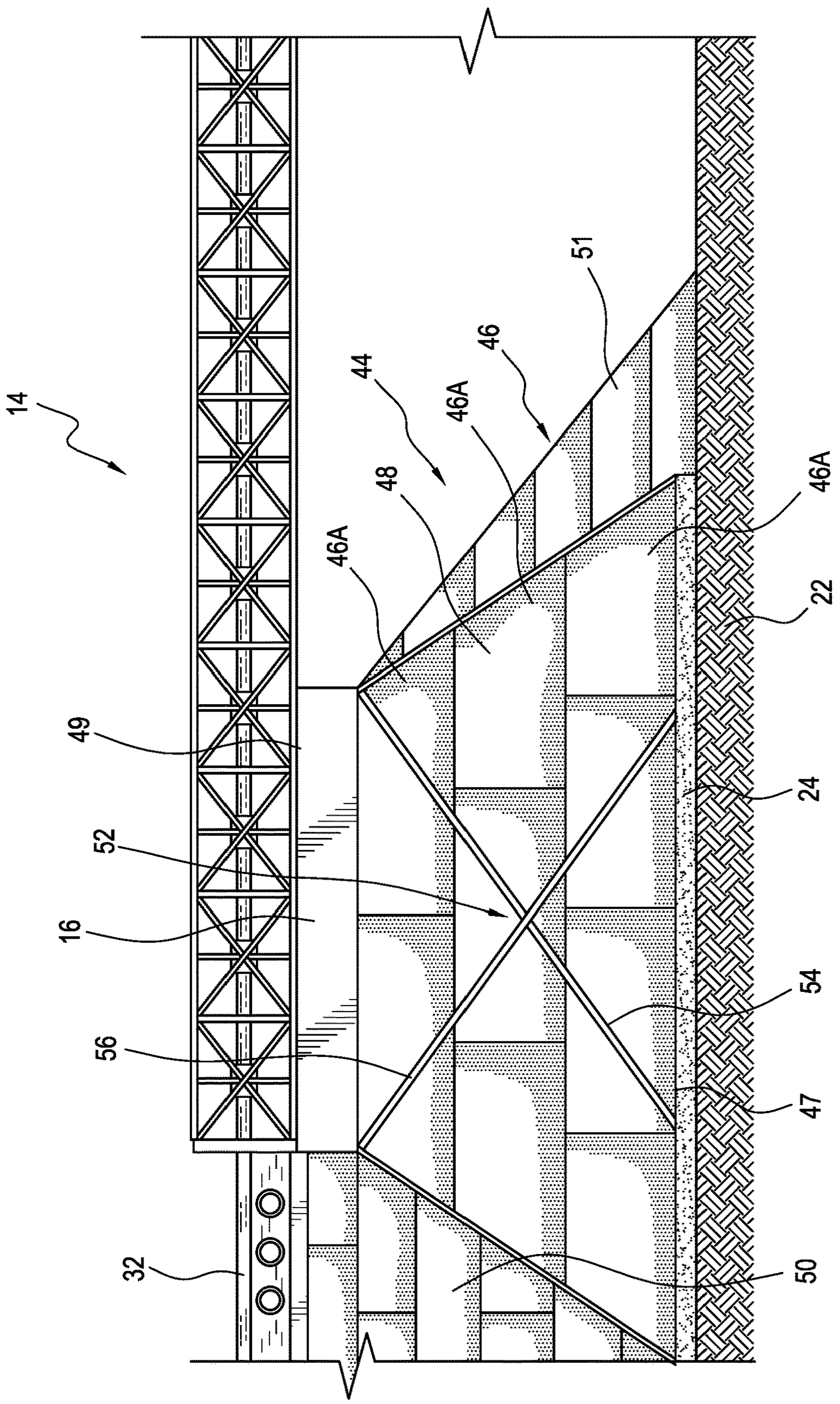


FIG. 7

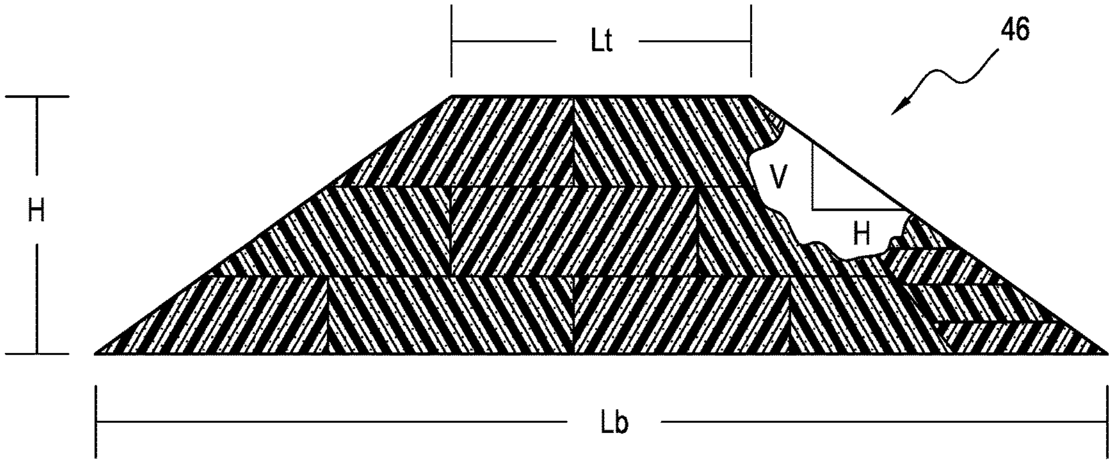


FIG. 8

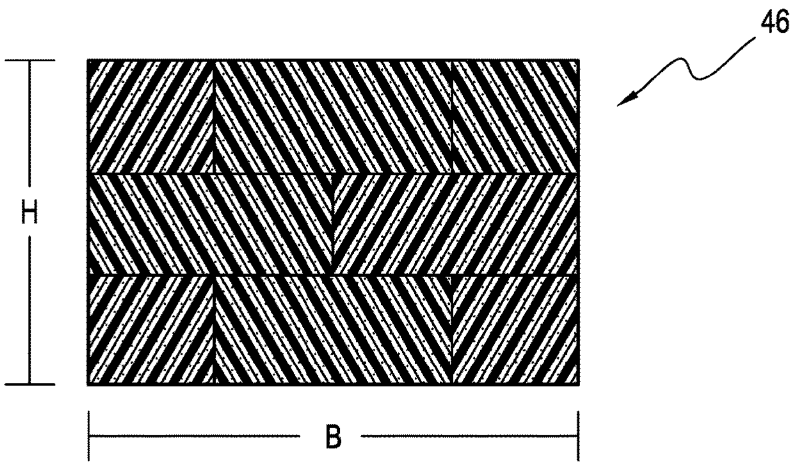


FIG. 9

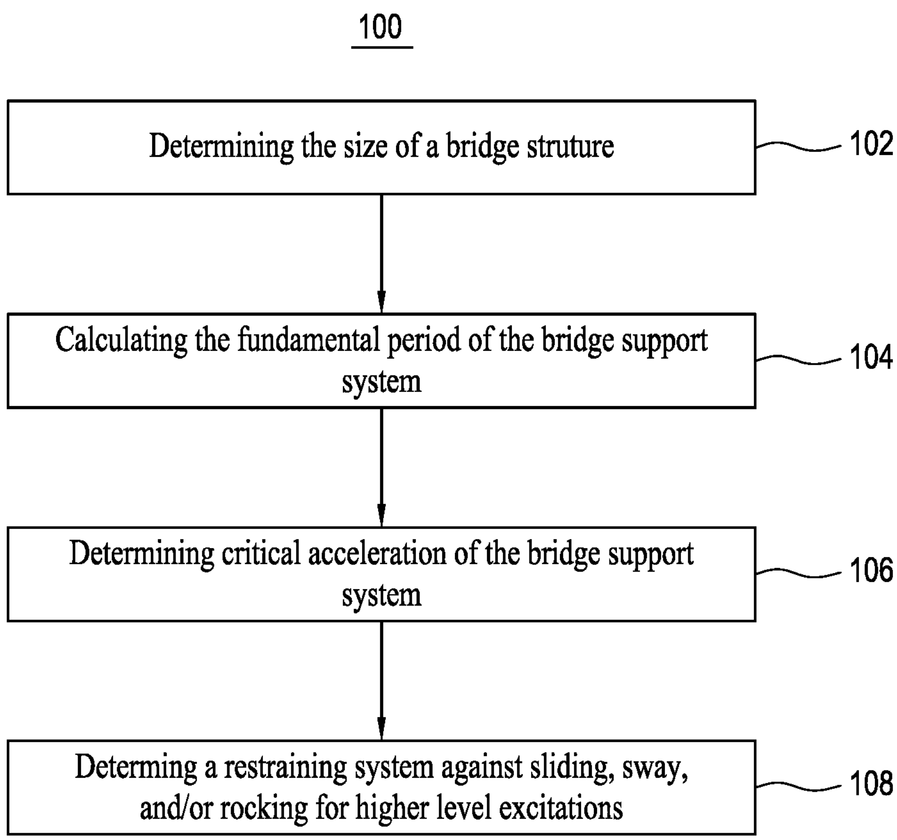

100
Determining the size of a bridge struture
102
Calculating the fundamental period of the bridge support system
104
Determining critical acceleration of the bridge support system
106
Determing a restraining system against sliding, sway, and/or rocking for higher level excitations
108

FIG. 10

Material	Lane	Width of bridge	Type of EPS	Length of bridge
----------	----------	m	----------	m
Steel	Single	5.25	22	20
Steel	Double	9	22	18
Steel	Single	5.25	29	34
Steel	Double	9	29	31
Concrete	Single	5.25	22	12
Concrete	Double	9	22	11
Concrete	Single	5.25	29	21
Concrete	Double	9	29	18

FIG. 11

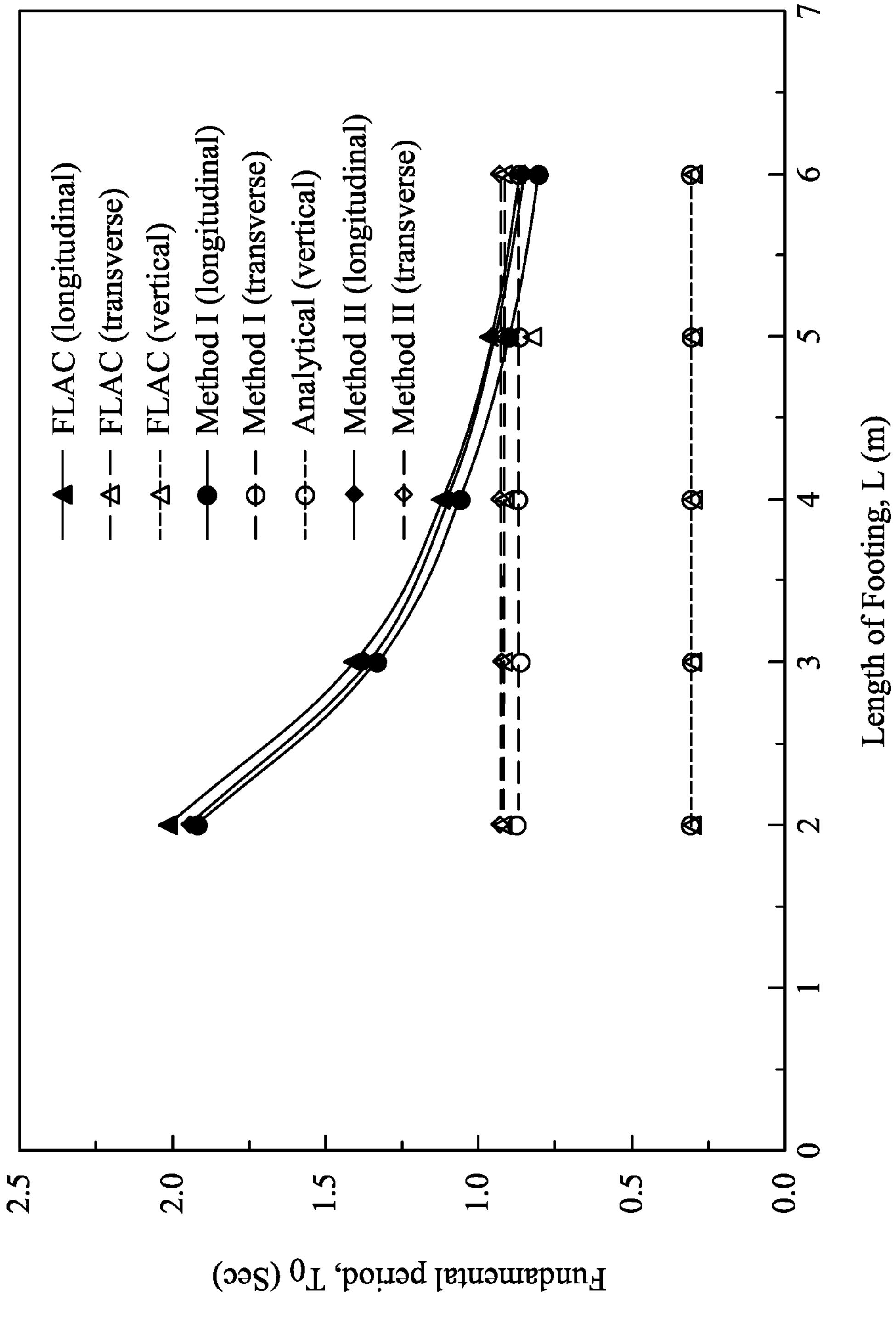

FLAC (longitudinal)
FLAC (transverse)
FLAC (vertical)
Method I (longitudinal)
Method I (transverse)
Analytical (vertical)
Method II (longitudinal)
Method II (transverse)
Fundamental period, T_0 (Sec)
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
7
Length of Footing, L (m)

FIG. 12

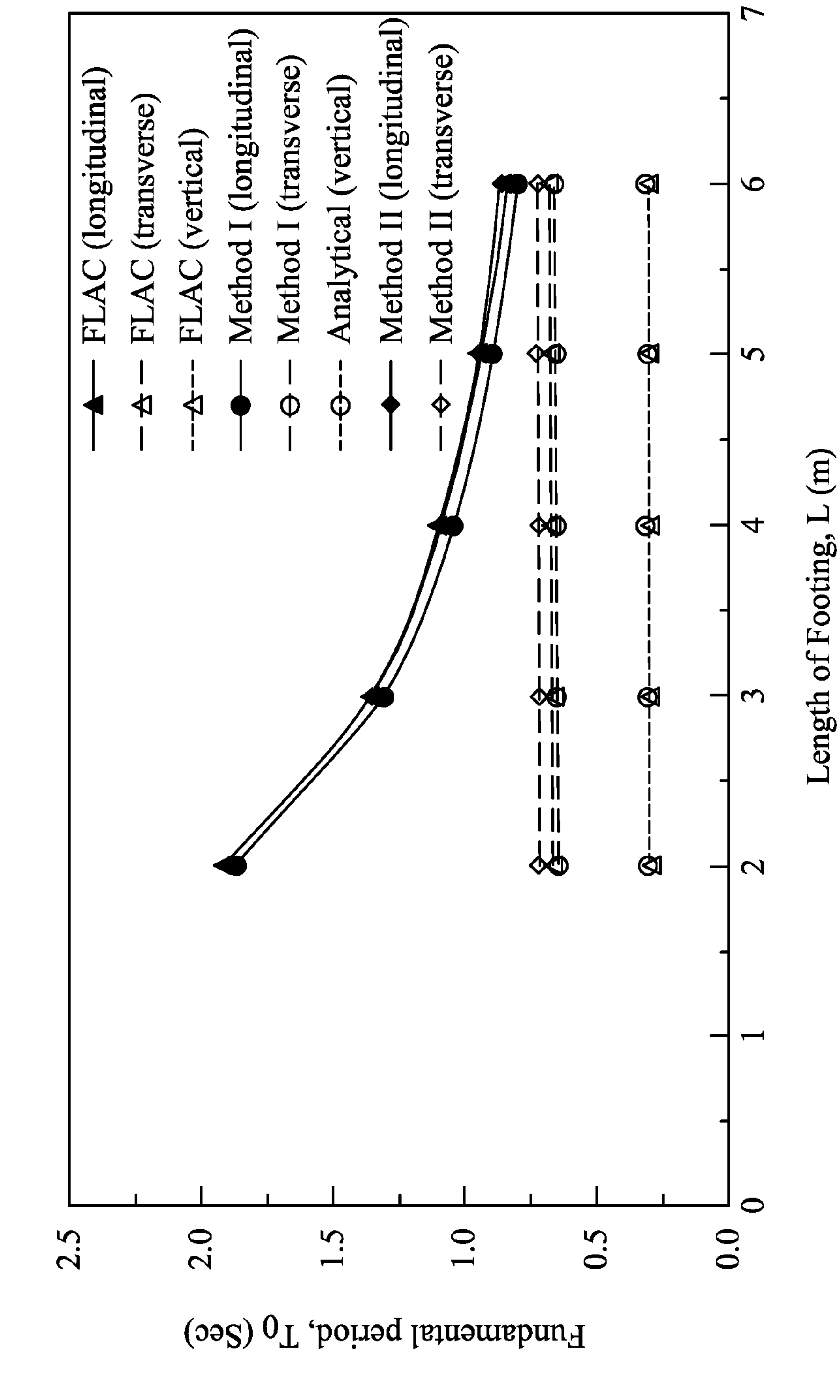

FLAC (longitudinal)
FLAC (transverse)
FLAC (vertical)
Method I (longitudinal)
Method I (transverse)
Analytical (vertical)
Method II (longitudinal)
Method II (transverse)
Fundamental period, T_0 (Sec)
0.0
0.5
1.0
1.5
2.0
2.5
0
1
2
3
4
5
6
7
Length of Footing, L (m)

FIG. 13

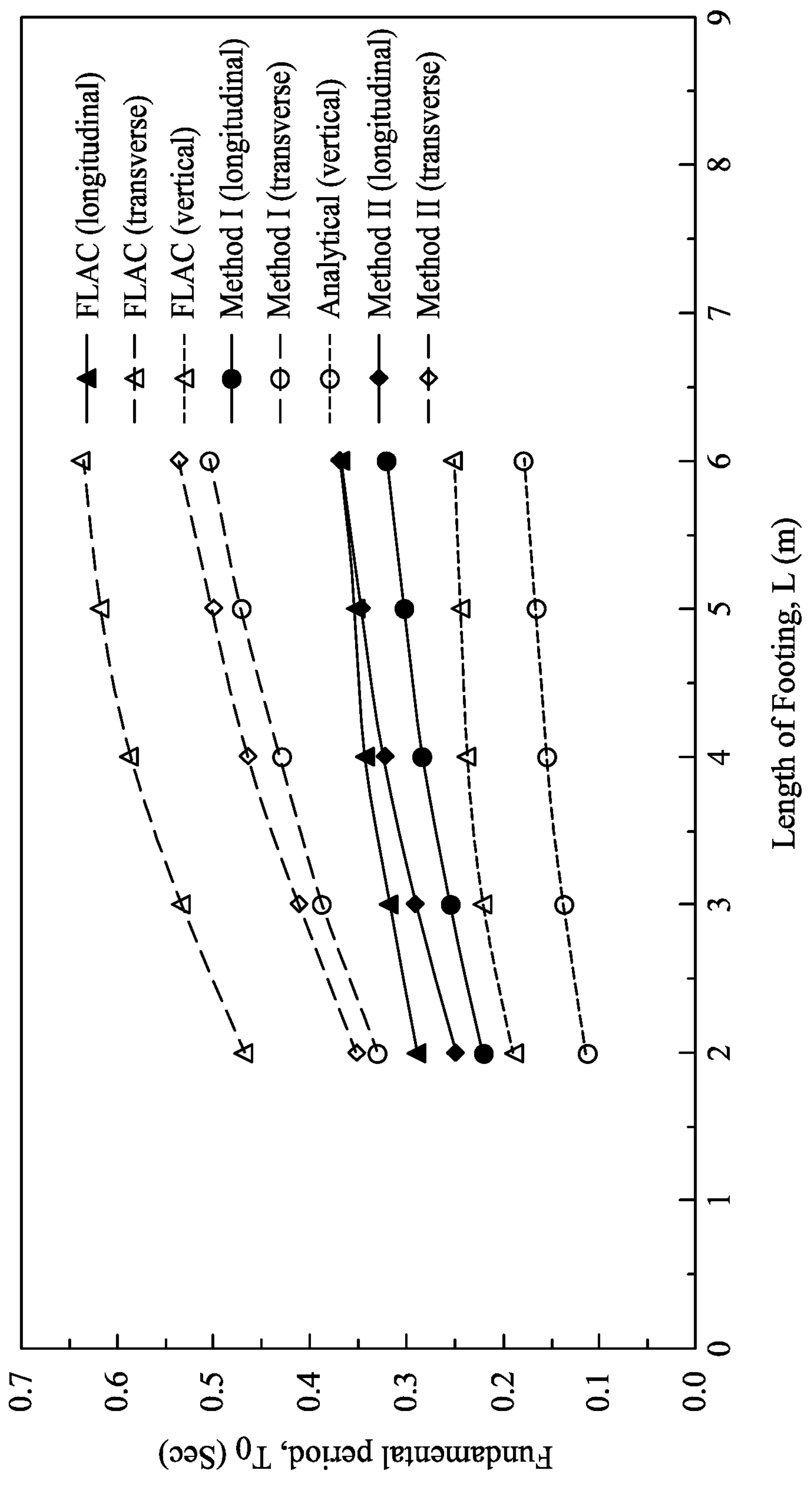

FLAC (longitudinal)
FLAC (transverse)
FLAC (vertical)
Method I (longitudinal)
Method I (transverse)
Analytical (vertical)
Method II (longitudinal)
Method II (transverse)
Fundamental period, T_0 (Sec)
Length of Footing, L (m)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
1
2
3
4
5
6
7
8
9

FIG. 14

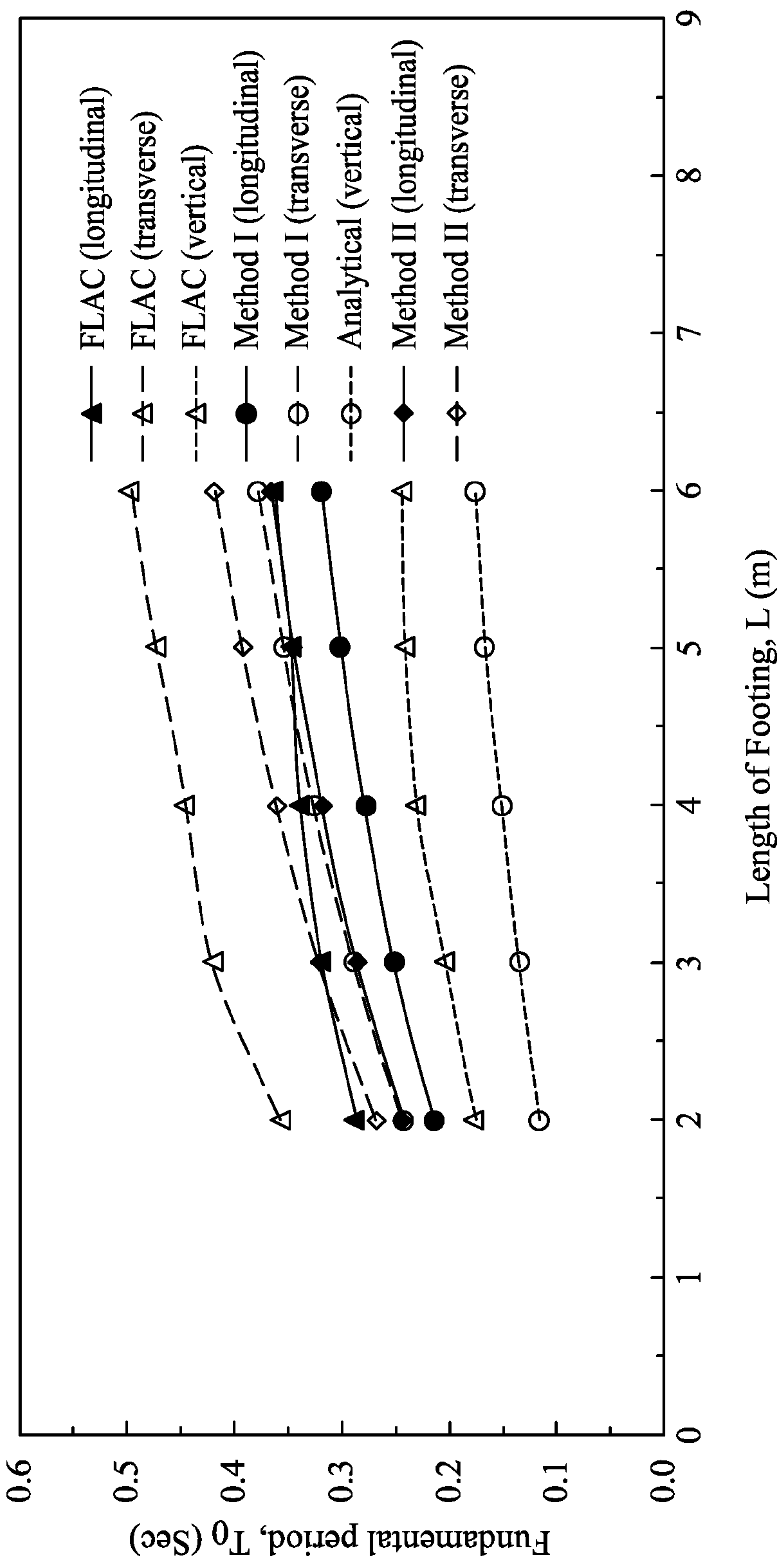

FLAC (longitudinal)
FLAC (transverse)
FLAC (vertical)
Method I (longitudinal)
Method I (transverse)
Analytical (vertical)
Method II (longitudinal)
Method II (transverse)
Fundamental period, T_0 (Sec)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Length of Footing, L (m)
0
1
2
3
4
5
6
7
8
9

FIG. 15

Footing length	Critical acceleration for single lane		Critical acceleration for double lane	
	Rectangular	Trapezoidal	Rectangular	Trapezoidal
m	*g*	*g*	*g*	*g*
2	0.6	0.6	0.6	0.6
4	0.6	0.6	0.6	0.6
6	0.6	0.6	0.6	0.6

FIG. 16

LIGHT-WEIGHT BRIDGE SUPPORT SYSTEMS AND METHODS OF USE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of and priority to U.S. Provisional Patent Application Ser. No. 62/253,439, filed Nov. 10, 2015, entitled "GEOFOAM BRIDGE SUPPORT SYSTEMS AND METHODS OF USE," and U.S. Provisional Patent Application Ser. No. 62/282,665, filed Aug. 6, 2015, entitled "EXPANDED POLYSTYRENE (EPS) GEOFOAM BRIDGE SUPPORT SYSTEM FOR ACCELERATED BRIDGE CONSTRUCTION," each of which are hereby incorporated herein in its entirety by this reference.

BACKGROUND

[0002] Accelerated construction of support systems for bridge structures on soft soil is very challenging. For instance, large consolidation and post-construction creep settlement tend to be major issues in such a case. In addition, low bearing capacity, poor construction conditions, relocation of buried utilities, and potential settlement damage to adjacent structures and foundations are also common issues that must be addressed in the construction and design of such systems.

[0003] Some attempts have been made to address these challenges by altering foundation conditions with some form of ground improvements or by constructing deep foundations (e.g., piles, shafts, etc.). However, such construction techniques are known to suffer from a number of drawbacks. For instance, construction of deep foundation systems is rather a general solution, but it slows down construction as loading (i.e., surcharging) of approach fills and waiting for consolidation of the foundation soil require considerable time and effort before completing final construction. This results in construction that is more expensive in terms of time and labor. In addition, while the construction of a deep foundation system can decrease the likelihood of undesirable settlement of the bridge structure itself, the construction of the associated earthen embankment increases the likelihood of collateral damage or having to relocate buried utilities and facilities.

[0004] There is thus a need for an improved bridge support system for soft or challenging soil sites which is less expensive to construct, and can be constructed in less time without the need of deep foundation systems and the associated earthen or retained earth approach embankment.

SUMMARY OF THE DISCLOSURE

[0005] In an embodiment, a bridge support system includes a support embankment formed from at least one light-weight material and arranged to support and be positioned under a footing of a bridge structure. A restraining system is operatively connected to the embankment. The restraining system includes cross-members which are angularly offset from each other and arranged to limit at least one of lateral and vertical movements of the support embankment under high level excitation.

[0006] According to a variation, the at least one light-material can comprise at least one of geofoam, light-weight cellular concrete, or geosynthetic reinforced soil.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] These and other features, aspects, and advantages of the present disclosure will become better understood regarding the following description, appended claims, and accompanying drawings.

[0008] FIG. **1** is a schematic view of a bridge support system including a support embankment according to an embodiment.

[0009] FIG. **2** is a partial cross section of a bridge support system including a support embankment according to another embodiment.

[0010] FIG. **3** is a cross section taken in longitudinal direction of the support embankment shown in FIG. **2**.

[0011] FIG. **4** is a cross section taken in a transverse direction of the support embankment shown in FIG. **2**.

[0012] FIG. **5** is a partial cross section of a support embankment according to another embodiment.

[0013] FIG. **6** is a partial cross section of a support embankment according to another embodiment.

[0014] FIG. **7** is a partial cross section of a bridge support system including a support embankment according to another embodiment.

[0015] FIG. **8** is a cross section taken in a longitudinal direction of the support embankment shown in FIG. **7**.

[0016] FIG. **9** is a cross section taken in a transverse direction of the support embankment shown in FIG. **7**.

[0017] FIG. **10** is an overview of the steps in an embodiment of a bridge design method using a bridge support system including a support embankment.

[0018] FIG. **11** is a table depicting results of designing a bridge according to an embodiment.

[0019] FIG. **12** is a graph depicting fundamental period results for a single lane bridge using a rectangular prismatic shape geofoam support embankment embodiment.

[0020] FIG. **13** is a graph depicting fundamental period results for a double lane bridge using a rectangular prismatic shape geofoam support embankment embodiment.

[0021] FIG. **14** is a graph depicting fundamental period results for a single lane bridge using a trapezoidal prismatic shape geofoam support embankment embodiment.

[0022] FIG. **15** is a graph depicting fundamental period results for a double lane bridge using a trapezoidal prismatic shape geofoam support embankment embodiment.

[0023] FIG. **16** is a table depicting critical acceleration for interlayer sliding results of a geofoam support embankment according to an embodiment.

DETAILED DESCRIPTION

[0024] A better understanding of different embodiments of the disclosure may be had from the following description read with the accompanying drawings in which like reference characters refer to like elements.

[0025] While the disclosure is susceptible to various modifications and alternative constructions, certain illustrative embodiments are in the drawings and described below. It should be understood, however, there is no intention to limit the disclosure to the embodiments disclosed, but on the contrary, that the intention covers all modifications, alternative constructions, materials, combinations, and equivalents falling within the spirit and scope of the disclosure.

[0026] For further ease of understanding the embodiments of a bridge support system as disclosed herein, a description of a few terms is necessary. The terms "rigid," "flexible," and "resilient" may be used herein to distinguish characteristics of portions of certain features of the bridge support system. The term "rigid" is intended to denote that an element of the system is generally devoid of flexibility. Within the context of support members that are "rigid," it is intended to indicate that they do not lose their overall shape when force is applied, and that in fact they may break if bent with sufficient force. On the other hand, the term "flexible" is intended to denote features that are capable of repeated bending such that the features may be bent into retained shapes or the features do not retain a general shape. The term "resilient" is used to qualify such flexible features as generally returning to an initial general shape without permanent deformation. As for the term "semi-rigid," this term is used to connote properties of support members that provide support and are free standing; however, such support members may have some degree of flexibility or resiliency.

[0027] The support system described is configured for use with bridge structures, such as single or two-lane highway bridges. It should be remembered, however, that the same concepts and methods may be similarly used for railroads, freeway ramps, roadways, pedestrian ramps and overpasses and other transportation engineering applications and are not limited solely to the bridge structures discussed.

[0028] The support system **3** of the present disclosure is described for use with a bridge or overpass structure **5** as shown in FIG. **1**. In an embodiment, the bridge structure **5** can include a pair of footings **7**. At least one beam, girder, truss, or pipe **9** can be attached to and extends across a span S defined between the footings **7**. The footings **7** are arranged to transfer loads from the bridge structure **5** to the support system **3** as described in more detail below.

[0029] The at least one beam **9** can support a deck **11**. The deck **11** is a component of the bridge structure **5** which is driven or traveled upon. The deck **11** can include shoulders, one lane, two lanes, a sidewalk, or any other suitable transportation or conveyance feature. It should be appreciated that many configurations of the bridge structure **5** may be used with the support system **3**. The bridge structure **5** and support system **3** may be collectively referred to as a bridge system **1**.

[0030] Because loads from bridge systems are relatively high and bridge systems typically must be designed for seismic performance, the construction of such systems on soft or problematic soil can be very challenging. For instance, many areas are plagued with ground issues that hamper or limit the use of conventional embankment and bridge support construction (e.g., issues associated with large consolidation and post-construction creep settlement, low bearing capacity, slope and embankment instability, poor construction conditions, relocation of burred utilities, and settlement damage to adjacent structures and foundations).

[0031] Some attempts have been made to address these challenges by altering foundation conditions with some form of ground improvements or by constructing deep foundations (e.g., piles, shafts, etc.). However, such construction techniques are extensive in scope and expensive in terms of time and labor, making them impractical in many applications.

[0032] To combat these problems, the present disclosure provides a support system **3** that includes a support embankment **4** formed of one or more light-weight materials for directly supporting the bridge structure **5** without the need of installing intermediate or deep foundation systems or using deep ground improvement to stabilize the foundation soils. This beneficially can contribute to accelerated bridge construction ("ABC") technologies for many classes and sizes of bridge structures as the support embankment **4** can be quickly and safely constructed atop challenging ground or site conditions.

[0033] In addition, the support system **3** of the present disclosure can be more easily constructed near buried utilities or nearby structures or facilities because of the reduced risk of collateral damage to such utilities and structures. This is yet another benefit that may help lead to more rapid and economical deployment of bridge foundations for permanent and temporary bridge structures.

[0034] The support embankment **4** is preferably formed of Expanded Polystyrene (EPS) geofoam blocks but any suitable light-weight, semi-rigid material is possible (e.g., other types of foams such as extruded polystyrene, plastics, light-weight cellular concrete and/or other types of light-weight earthen materials). EPS geofoam and light-weight cellular concrete are light-weight materials available in many different densities and strengths. It should be appreciated that the support embankment **4** is substantially less dense than traditional earthen embankment fill materials such as rock and soil. This has the effect of decreasing the overall load of the bridge system **1**, which, in turn, helps reduce the likelihood of undesirable settlement.

[0035] In addition, because the support embankment **4** is less dense than traditional embankments, it can be constructed on soil exhibiting lower bearing capacities, thus improving settlement and stability performance of the bridge system **1** and potentially eliminating costs associated with deep foundation systems.

[0036] Another advantage of the support embankment **4** is that it can include a restraining system **6** for improving the seismic performance of the support system **3**. The restraining system **6** can limit the development of stresses in the light-weight materials forming the support embankment **4** (e.g., geofoam blocks) associated with high level excitation (e.g., seismic excitation, wind excitation, blast excitation, etc.) of the support system **3**. In bridge support systems, embankments generally can be overstressed from three different loading conditions: types of loads (dead and live), seismic excitation, and duration of loading (short term and long term).

[0037] When considering extreme events like earthquakes and/or explosive blasts in design, the embankment **4** can include a semi-rigid configuration arranged to restrain against the associated forces which include rigid body translation (i.e., sliding). EPS geofoam and light-weight cellular concrete have been used in transportation engineering applications as an alternative to earthen, geo-synthetic reinforced soil ("GRS") and mechanically-stabilized earth ("MSE") systems when deployed as approach embankment for highway bridges located atop soft or challenging soil sites. The application of light-weight materials to directly support a bridge structure however has been very limited due to unconfirmed or unpredictable seismic performance of the EPS geofoam. As such, the support embankments of the present disclosure provide a significant improvement over conventional bridge support systems in terms of seismic safety.

[0038] FIGS. **2-4** illustrate a support system **10** including a support embankment **12** constructed of one or more light-weight materials according to an embodiment. The support system **10** can be arranged to support a bridge structure **14** including at least one footing **16**, at least one main beam **18**, and a deck **20** supported at least in part by the main beam **18**. The bridge structure **14** can be a 2-lane highway, a single-span highway, a pedestrian bridge structure, and/or any other suitable type of transportation or conveyance structure. The bridge structure **14** can be constructed of steel, concrete, asphalt, wood, combinations thereof, or any other suitable material.

[0039] The support embankment **12** includes a bottom portion **13** arranged to be placed on foundation soil **22** and a top portion **15** engageable with a bottom of the footing **16**. The foundation soil **22** can be a soft soil.

[0040] According to a variation, the bottom portion **13** of the embankment **12** can be placed on a basal slab **24** arranged to distribute horizontal and vertical loads from the support system **10** and/or the bridge structure **14** over a larger area. It will be appreciated that the basal slab **24** can be embedded in the foundation soil **22** or can sit on top of the foundation soil **22**.

[0041] The support embankment **12** can be constructed of one or more light-weight materials. For instance, the support embankment **12** can include a plurality of geofoam blocks **26** stacked in one or more different layers **12**A. As seen, the geofoam blocks **26** of one layer **12**A may be staggered relative to the blocks of another layer **12**A. In an embodiment, the different layers **12**A can have the same height. In other embodiments, different layers **12**A can have different heights.

[0042] The geofoam blocks **26** may be formed of EPS and/or any other synthetic, construction or earthen material which would provide sufficient strength to resist undesirable deformation during implementation. For instance, the geofoam blocks **26** may be formed of EPS **22** or EPS **29**, or other mass densities (kg/m^3). It will be appreciated that in other embodiments the geofoam blocks **26** or other light-weight materials of the support embankment **12** can have higher or lower values of material properties in terms of compressive strength and modulus.

[0043] The geofoam blocks **26** can be high density EPS (e.g., EPS **22** and greater), helping in the support of the footing **16** of the bridge structure **14**. According to a variation, the support embankment **12** can include a second plurality of geofoam blocks **28** below a load distribution slab located under road pavement **32** approaching the bridge structure **14** and substantially adjacent to the geofoam blocks **26**. The second geofoam blocks **28** can be a lower density EPS to support the roadway pavement **32**.

[0044] The different densities of EPS in the support embankment **12** advantageously help accommodate differential loading of the bridge structure **14** and the roadway pavement **32**, the load from the bridge structure **14** being much higher than from the roadway pavement **32**.

[0045] At the interface of the two systems of EPS blocks, a joint **34** can be arranged to reduce stress and interaction. Due to the difference in loadings, a floating slab **36** may be placed between the footing **16** of the bridge structure **14** and the load distribution slab of pavement **32**.

[0046] As noted above, the support embankment **12** is arranged to support loads associated with the bridge structure **14** and transferred to the support embankment **12** via the footing **16**. Horizontal loads from seismic events and other mechanisms (e.g., vehicular impact, blasts, wind, etc.) may be transferred from footing **16** to the basal slab **24** via a restraint system described below, as necessary for a specific application.

[0047] The mass density of the light-weight approach and support embankment embodiments can be significantly less than other conventional geotechnical materials like soil and rock. As such, the support embankment **12** can be more easily constructed atop foundation soils without having to substantially alter soil conditions. This advantageously can contribute to the rapid construction of certain classes and sizes of bridge structures and overpasses. For instance, the support embankment **12** can be constructed on softer soils without the support of deep foundation systems as in the prior art, reducing construction time and expenses. In addition, the support embankment **12** can be constructed near buried utilities or nearby structures with less concern about collateral damage.

[0048] In addition to being lightweight, a beneficial characteristic of the support embankment **12** is its capacity to support the associated dead and live loads of the bridge structure **14** without being overstressed. The dead loads can comprise the dead load by the footing **16**, the deck **20**, and the beam or main column **18**. The live loads can comprise cyclic and impact vehicular loads, and extreme loading events, such as those from earthquake events. For extreme events, the support system **10** must handle forces associated with sliding, sway, and rocking of the bridge structure **14** and/or the support system **10** itself.

[0049] In an embodiment, the support system **10** includes a restraining system **38** arranged to help the support embankment **12** handle seismic excitation or other horizontal and vertical design forces. More particularly, the restraining system **38** is arranged to help limit lateral and vertical movement of the support embankment **12** at high levels of seismic excitation, as necessary for a particular application.

[0050] According to a variation, the restraining system **38** can include a first member **40** and a second member **42** placed externally on the support embankment **12**. The first and second members **40**, **42**, respectively, can be arranged in between the footing **16** and the basal slab **24**. The first and second members **40**, **42** can be cables, threaded bars, fiber reinforced polymer ("FRP") rods, or any other suitable member.

[0051] Multiple crisscrossing arrangements may be used.

[0052] The first and second members **40**, **42** can be diagonal cross-members which are angularly offset from each other. For instance, the first and second members **40**, **42** can crisscross between the footing **16** and the basal slab **24** and/or foundation soil **22**. As seismic or other events tend to force the support embankment **12** to move laterally, the first and second members **40**, **42** can be placed in alternating tension and/or compression. For instance, the first member **40** can be stretched and placed in tension as the support embankment **12** tends to move laterally in one direction, thereby elongating the first member **40**.

[0053] In contrast, the second member **42**, can be placed under compression if it has a rigid or semi-rigid configuration; thereby reducing a length of the second member **42** from its equilibrium length, or reducing the tension in the second member **42** for example if flexible cabling is used. It will be appreciated that a force which tends to cause the support embankment **12** to move may also oscillate. In such a manner, the first and second members **40** and **42** may alternatively move from tension to compression. Accordingly, to reduce, and possibly eliminate, much of the excessive movement of the embankment **12**, a significant portion of the seismic forces may be transferred and concentrated in the first and second members **40**, **42** and ultimately transferred to the basal slab **24** and into the surrounding foundation soil **22**. Hence, the members or elements **40** and **42** act as a secondary stiffness damper system ("SSD").

[0054] This complex interaction between the footing **16** and the basal slab **24** via the support embankment **12** and the first and second members **40**, **42** advantageously improves the dynamic performance of the support system **10** by limiting the development of associated movement and/or deformation in the embankment **12** during seismic or other excitation. This is a significant improvement over known support systems whose behavior during seismic events may be unacceptable or is unpredictable. It will be appreciated that the first and second members **40**, **42** can be adapted to help resist horizontal translation, lateral sway and rocking.

[0055] If the foundation soil **22** is highly compressible, the foundation soil **22** may be connected to the basal slab **24** to provide transfer of seismic forces to the adjacent and underlying soil.

[0056] Referring to FIGS. **2-4**, the support embankment **12** can have a generally rectangular prismatic shape according to an embodiment. For instance, the support embankment **12** can define a length L extending in a direction generally parallel to a longitudinal axis of the bridge structure **14**, a width B extending generally transverse to the longitudinal axis of the bridge structure **14**, and a height H extending between the footing **16** and the basal slab **24** or foundation soil **22**. The width B of the support embankment **12** can be substantially the same or greater than a width of the footing **16**.

[0057] According to a variation, the basal slab **24** can have a length generally corresponding to the length L of the support embankment **12** and the length of the joint **34**. In other embodiments, the basal slab **24** can have length generally corresponding to the length L of the support embankment **12**. In yet other embodiments, the basal slab **24** can have a greater length than the support embankment **12**.

[0058] An area of the support embankment **12** at its top can be substantially the same as the bottom area of the footing **16**. The height H of the support embankment **12** can be selected based on a particular application. The height H of the support embankment **12** can be about 4 m, 6 m, 8 m, 10 m or any other suitable height. The shape of the support embankment **12** can affect vertical stress distribution.

[0059] It will be appreciated that the type of light-weight material and size of the footing **16** at least in part determine the length of bridge structure that can be supported by the support system **10**. For example, the length of the bridge structure **14** can be increased with the use of higher strength and stiffness of the light-weight material. The seismic performance of the support system **10** may also be improved likewise.

[0060] The support embankment **12** can include one or more features to limit or prevent interlayer or internal sliding. For instance, different layers **12**A of the support embankment **12** can be attached to one another via an adhesive or mechanical fasteners, helping to prevent interlayer sliding. For other materials, such as light-weight cellular concrete, reinforcement or other mechanical means may be deployed.

[0061] A support embankment **62** according to another embodiment is shown in FIG. **5**. The support embankment **62** and its associated restraining system can include one or more shear keys **30** arranged among the geofoam blocks **26** to interrupt the formation of continuous horizontal slide planes during seismic or other high level excitation. The shear keys **30** can provide cohesive resisting force. The shear keys **30** can comprise half-height EPS blocks or any other suitable structure or material. The shear keys **30** can be used in between the layers where the factor of safety against sliding was less than 1.1. In earthquake design, the structure is considered safe if the factor of safety against interlayer sliding is in the range of 1.1 to 1.2. The size and number of shear keys **30** can be selected based on the geofoam shear strength and shear coverage.

[0062] A support embankment **64** according to another embodiment is shown in FIG. **6**. The support embankment **64** can include one or more features to limit or prevent basal sliding. For instance, a bottom portion **66** of the support embankment **64** can be embedded in the foundation soil **22**. The depth D of embedment may vary based on the application. For instance, the depth of embedment may be between 0.5 m and 3 m or between about 1 m and about 2 m. Optionally, shallow ground improvement, cemented treated soil, anchors or excavation, replacement and compaction of granular materials may be used around and/or below the basal slab **24** to improve sliding resistance of the embankment **64**.

[0063] When the support embankment **64** is embedded in the foundation soil **22**, the seismic passive forces provide the resistance for sliding. When seismic excitation takes place, the embedment of the embankment **64** along the leading side of excitation produces the passive earth pressure and the trailing side produces the active earth pressure.

[0064] Because the support embankment **64** can be restrained against sliding (i.e., rigid-body translation), sway and rocking associated with extreme seismic events, the support system of the present disclosure advantageously increases the possibility of substantial advancement in ABC technologies for certain classes and sizes of bridge structures.

[0065] FIGS. **7-9** illustrate a bridge support system **44** according to another embodiment. As seen, the support system **44** can be similar to the bridge support system **10**. The support system **44** includes a support embankment **46** including at least one light-weight material for supporting the bridge structure **14**. For instance, the support embankment **46** can include a plurality of geofoam blocks **48**.

[0066] The support embankment **46** can have a trapezoidal configuration including a bottom portion **47** positioned on the foundation soil **22** and/or the basal slab **24** and a top portion **49** engaging a bottom of the footing **16**.

[0067] Similar to the other embodiments, the geofoam blocks **48** of the support embankment **46** can be arranged or stacked in one or more different layers **46**A. As seen, the geofoam blocks **48** of one layer **46**A may be staggered relative to the blocks **48** of another layer **46**A. The layers **46**A can have the same or different heights. The geofoam blocks **48** can include any type of EPS. For instance, the geofoam blocks **48** can be EPS **12**, EPS **15**, EPS **19**, EPS **22**, EPS **29**, EPS **39**, EPS **46**, or any other type of geofoam.

[0068] According to a variation, the support embankment **46** can include a second plurality of geofoam blocks **50**. The second geofoam blocks **50** can be positioned below a load distribution slab under the road pavement **32** approaching the bridge structure **14** and along a side slope of the geofoam blocks **48**. The second geofoam blocks **50** can be lower density EPS, helping to support the lower load of the road pavement **32** at a lower expense. A third plurality of geofoam blocks **51** can be positioned along the opposite slide slope of the geofoam blocks **48**. The third geofoam blocks **51** can help stabilize the geofoam blocks **48**.

[0069] The support system **44** can include a restraining system **52** arranged to help the support embankment **46** handle seismic or other extreme excitation events (e.g., wind, blasts, etc.). The restraining system **52** can include a first member **54** and a second member **56** placed externally on the support embankment **46**. The first and second members **54**, **56** can be arranged in between the footing **16** and the basal slab **24**. The first and second members **54**, **56** can be diagonal cross-members which are angularly offset from each other. As a seismic or other event tends to force the support embankment **46** to move laterally and vertically, at least part of the associated stresses can be concentrated in the restraining system **52**, rather than in the support embankment **46**, improving the dynamic performance of the support embankment. The first and second members **54**, **56** can be cables or any other suitable member.

[0070] The support embankment **46** is shown having a trapezoidal prismatic shape but can have any suitable shape. For example, the support embankment **46** can define a bottom length Lb and a top length Lt extending in a general direction parallel to the longitudinal axis of the bridge structure **14**, and a height H extending between the footing **16** and the basal slab **24** or the foundation soil **22**. The height H can be 4 m, 6 m, 8 m, 10 m, or any other height. In an embodiment, the basal slab **24** can have a length generally corresponding to the bottom length Lb of the support embankment **62** or a length that is greater or smaller than the bottom length Lb of the support embankment **62**.

[0071] As seen, the bottom length Lb is greater than the top length Lt, which, in turn, creates side slopes on the support embankment **46**. The side slopes can include a vertical component V and a horizontal H component. In an embodiment, the side slope can have a ratio of 1 V:2 H, or any other ratio, as determined by geometrical constraints or other design and construction considerations.

[0072] The support embankment **46** can also define a width B extending generally transverse to the longitudinal axis of the bridge structure **14**. As seen, the transverse cross section of the support embankment **46** can have a generally rectangular shape.

[0073] The shape of the support embankment embodiments can influence the fundamental period. For the seismic design, the fundamental period of structures is paramount because the embankment systems generate the maximum acceleration when excited at the fundamental period. Fundamental period is used herein to refer to the time at which the embankment moves one cycle back and forth under free vibration.

[0074] The fundamental period can be used for the determination of the peak inertial force experienced by the system using the design acceleration at that period obtained from an acceleration response spectra, as is the case for site specific design;

[0075] or the inertial force may be assumed in more general design. The inertial force is calculated by using Newton's second law of motion as the product of mass of the system and spectral acceleration at the fundamental period of the support system. Once the force at the top of the embankment is known, the safety factor of the bridge support system can be determined for modes of potential failure (as discussed below) using commonly accepted techniques.

[0076] The dynamic response of the support embankment embodiments can be very complex at high levels of seismic excitation. The material forming the embankment is generally semi-rigid, but becomes more flexible as it undergoes strain and yields during cycling. As such, the support embankment can absorb large amounts of energy associated with excitation. Possible modes of excitation and failure can include (1) rigid-body translation (sliding), (2) horizontal flexibility and shear deformation (lateral sway), and (3) rigid-body rotation (seismic rocking).

[0077] FIG. **10** is an overview of the steps in an embodiment of a bridge design method **100** using a bridge support system embodiment of the present disclosure. The method **100** includes the step **102** of determining the size of a bridge structure. Step **102** can include, for example, selecting the type of EPS, the size and material of the footings, the shape of the support embankment, and calculating dead and live loads.

[0078] Additionally, FIG. **10** shows that the method **100** can include a step **104** of calculating the fundamental period of the bridge support system. For instance, the fundamental period can be calculated considering excitation along the direction of the bridge structure, across or transverse to the bridge structure, and the upward direction. These excitations can be denoted by longitudinal, transverse, and vertical directions.

[0079] The method can include the step **106** of determining the critical acceleration of the bridge support system. Critical acceleration is the acceleration at which the factor of safety is equal to unity for the respective modes of excitation or failure (e.g., sliding, lateral sway, and rocking) without the deployment of a seismic restraining system.

[0080] Finally, the method **100** can include the step **108** of determining a restraining system against sliding, sway, and/or rocking for higher levels of excitation. This may include determining the details of a restraint system for higher levels of excitation and/or an improved factor of safety obtained from the restraining system. Additional details and exemplary methods for designing a bridge system including a light-weight bridge support embodiment can be found in U.S provisional application 62/282,665, filed on Aug. 6, 2015, the disclosure of which is incorporated herein by this reference.

[0081] FIG. **11** illustrates exemplary results of designing a bridge using a geofoam support embankment. The results assume the use of steel and concrete and EPS **22** and EPS **29** embankment materials for footing of length 4 m. As seen, if steel is used for the bridge, the maximum length of the bridge using EPS **22** according to an embodiment is about 20 m and about 18 m, respectively, for single and double lanes. Spans of greater length are possible for both bridge types (steel or concrete) using higher densities of EPS blocks.

[0082] FIGS. **12** and **13** illustrate exemplary fundamental period results using the geofoam support embankment embodiment having a rectangular shape when it is excited in three directions for single and double lanes. More particularly, FIG. **12** illustrates the fundamental period of a rectangular prismatic shape embankment embodiment from numerical and analytical methods at various lengths of footing for a single lane bridge. FIG. **13** illustrates the fundamental period of the same embankment embodiment for a double lane bridge. As seen, the fundamental period can decrease with increased length of footing when the seismic excitation is introduced along that direction.

[0083] In the numerical and analytical methods, the mass above the geofoam support embankment and the support embankment itself was assumed constant for all cases. So, the stiffness of the embankment depended on the dimensions of the embankment. Width and height remained constant, so stiffness increased with increased length and the fundamental period decreased, correspondingly. The fundamental period along transverse and vertical directions can be almost constant assuming width and height dimensions are constant.

[0084] For the single lane, the fundamental period along longitudinal-direction was higher than transverse-direction for the length less than width. Once the length exceeds the width, the fundamental period along the longitudinal-direction decreased.

[0085] Similar results were obtained for the double lanes. In double lane, the width exceeded length in all cases and the fundamental period was higher in the longitudinal-direction for all values of length. The fundamental period for the excitation along the longitudinal-direction was in the range of about 0.8 to about 2.0 sec. The value was smaller for greater length. The fundamental periods were around 0.9 sec and 0.3 sec for excitation along the transverse and vertical directions respectively.

[0086] FIGS. **14** and **15** illustrate exemplary fundamental period results using the geofoam support embankment embodiment having a trapezoidal prismatic shape when it was excited in three directions for single and double lane, respectively.

[0087] For the single and double lane, the fundamental period increased with increase in length. The fundamental period along the transverse-direction was larger than the longitudinal-direction. The average length of the trapezoidal section was larger than width for both single and double lane. As the distance of excitation increased, the stiffness of the embankment increased and the corresponding fundamental period decreased.

[0088] FIG. **16** illustrates exemplary critical acceleration results for interlaying sliding for rectangular and trapezoidal prismatic shaped geofoam support embankment embodiments without a restraining system. As seen, the critical acceleration for both of embankment embodiments is 0.6 g. According to an embodiment, performance of the method **100** determined that a geofoam support embankment constructed of EPS **29** may be overstressed during the lateral sway and rocking modes at horizontal accelerations of 0.2 g and 0.3 g, respectively, and that minor uplift at the basal corners of the support system was initiated during rocking once the horizontal excitation reached about 0.15 g to 0.2 g; however, this amount of uplift was relatively small and may not have any consequence. Nonetheless, the seismic performance in terms of basal and interlayer sliding, lateral sway and rocking can be significantly improved by the use of the restraining system embodiments, by using geofoam with densities higher than EPS **29**, and/or by using shear keys and/or adhesion of the blocks.

[0089] A restraining system that includes the first and second members or cables of the present disclosure can significantly reduce the potential for overstressing geofoam blocks by limiting the amount of sliding and shear strain that develops during lateral sway and rocking. According to an embodiment, performance of the method **100** determined that the cabling feature of the restraining system alone may increase the critical acceleration to about 1 g.

[0090] It will be appreciated that the embodiments described herein are to be regarded as exemplary only, as any bridge support system is possible. For instance, the support embankment embodiments may include sheet piling arranged to provide lateral support to the support embankment. In other embodiments, the bridge support system can include multiple embankment structures or assemblages of blocks placed under each footing such as geofoam blocks placed in shipping cargo containers or other means of containment, confinement or restraining of the individual blocks.

[0091] In other embodiments, the restraining system can include one or more members extending through or external to the support embankment. In other embodiments, the restraining system can include at least one member extending diagonally between the footing and the basal slab. In yet other embodiments, the first and second members of the restraining system can be arranged in a cross-like arrangement. In other embodiments, the restraining system can include a first pair of members crisscrossing between the footing and the basal slab and a second pair of members also crisscrossing between the footing and the basal slab. In other embodiments, the first and/or second members can be post tensioned or pre-tensioned.

[0092] In other embodiments, the restraining system can include members on both sides of the support embankment (e.g., on the right and left sides). In yet other embodiments, the restraining system can include three, four, five, six, or any other suitable number of members to help resist horizontal and/or vertical movement. In other embodiments, the restraining system can include a seismic damper. In an embodiment, the members of the restraining system can have a circular, rectangular, square, triangular, oval, elliptical, irregular, or any other cross section shape. In other embodiments, at least one of the members of the restraining system can have a two-part construction including a core surrounded by a sleeve portion.

[0093] In other embodiments, the bridge structure may comprise a pedestrian bridge. In other embodiments, the geofoam blocks may form only a portion of the support embankment. For instance, the geofoam blocks may be filed with a lightweight reinforcing material, such as concrete, cemented treated material, etc.

[0094] In other embodiments, the support embankment may have a parabolic shape, an L-shape, a U-shape, an irregular geometric shape, or any other suitable shape. The geofoam blocks are illustrated having a generally rectangular shape but can be formed in any suitable shape including shapes that interlock or interconnect.

[0095] While various aspects and embodiments have been disclosed herein, other aspects and embodiments are contemplated. For instance, the embankment embodiments described herein may be configured as approach embankments. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting. Additionally, the words "including," "having," and variants thereof (e.g., "includes" and "has") as used herein, including the claims, shall be open ended and have the same meaning as the word "comprising" and variants thereof (e.g., "comprise" and "comprises").

What is claimed is:

1. A bridge support system comprising:

a support embankment formed from at least one light-weight material and arranged to support and be positioned under a footing of a bridge structure; and

a restraining system operatively connected to the support embankment, the restraining system including cross-members which are angularly offset from each other and arranged to limit at least one of lateral and vertical movement of the support embankment under high level excitation.

2. The system of claim **1**, wherein the cross-members comprise diagonal cross-members extending between the footing and a basal slab under the support embankment.

3. The system of claim **1**, wherein the cross-members comprise cables or cabling.

4. The system of claim **1**, wherein the at least one light-weight material comprises at least one of geofoam, light-weight cellular concrete, or geosynthetic reinforced soil.

5. The system of claim **1**, wherein the at least one light-weight material comprises a plurality of geofoam blocks stacked in a plurality of layers.

6. The system of claim **5**, wherein the geofoam blocks are formed of Expanded Polystyrene (EPS).

7. The system of claim **5**, wherein the EPS is EPS **22** or EPS **29**.

8. The system of claim **5**, wherein the support embankment has a generally rectangular prismatic shape.

9. The system of claim **5**, wherein the support embankment has a generally trapezoidal prismatic shape.

10. The system of claim **5**, wherein the support embankment includes a bottom portion positionable on a soft soil.

11. The system of claim **5**, wherein the support embankment includes a bottom portion embedded in foundation soil below the support embankment.

12. The system of claim **7**, wherein the support embankment includes one or more shear keys arranged to interrupt the formation of continuous horizontal slide planes between adjacent ones of the layers of the geofoam blocks.

13. The system of claim **12**, wherein at least one of the shear keys comprises a half-height geofoam block.

14. The system of claim **5**, wherein at least some of the layers of the geofoam blocks are attached to one another via an adhesive to prevent interlayer sliding.

15. The system of claim **1**, further comprising a bridge structure including at least one footing positioned on a top portion of the support embankment.

16. A bridge system comprising:

a bridge structure including at least one footing;

a support embankment formed from geofoam material and directly supporting the bridge structure via the at least one footing engaging the support embankment; and

a restraining system operatively connected to the support embankment, and arranged to limit at least one of lateral and vertical movement of the geofoam embankment under seismic excitation.

17. The system of claim **16**, wherein the restraining system includes first and second members placed externally on the geofoam embankment.

18. The system of claim **17**, wherein the first and second members extend between the at least one footing and a basal slab under the geofoam embankment.

19. The system of claim **17**, wherein the first and second members are diagonal cross-members which are angularly offset from each other.

20. A bridge support system comprising:

a support embankment formed from a plurality of geofoam blocks stacked in a plurality of layers, the support embankment arranged to support and be positioned under a footing of a bridge structure;

one or more shear keys disposed between the geofoam blocks and arranged to interrupt the formation of continuous horizontal slide planes between adjacent ones of the layers of the geofoam blocks; and

a restraining system operatively connected to the support embankment, the restraining system including diagonal cross-members which are angularly offset from each other and arranged to limit at least one of lateral and vertical movement of the support embankment under high level excitation.

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