Finite Element Analysis and Constitutive Modelling in Geomechanics

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Lecture – 44
Mitigation of Soil Liquefaction using Granular Columns

I would like to show a couple of flips from the shaking table test. **(Video Starts: 00:00:24)** So, this first case is of untreated ground supporting the embankment the shaking has begun, so, it can be seen that the soil is fully liquefied and it has collapsed. This case corresponds to the ordinary column treated ground. So, during shaking the water gushing out of the granular column is able to be witnessed over here.

Unlike the previous case, where the soil had fully collapsed. So, in this case it had performed better. So, the water had come up through the granular columns. It is a case of encased granular column that is to be shown here, similar to the previous case of ordinary granular column treated ground. So, the water that gushes out of the granular column visible over here. **(Video Ends: 00:02:01)** Hi, in follow-up to the previous lecture that was titled on simulation of soil liquefaction using FLAC.

So, this lecture is delivered on the title of mitigation of soil liquefaction using granular columns.

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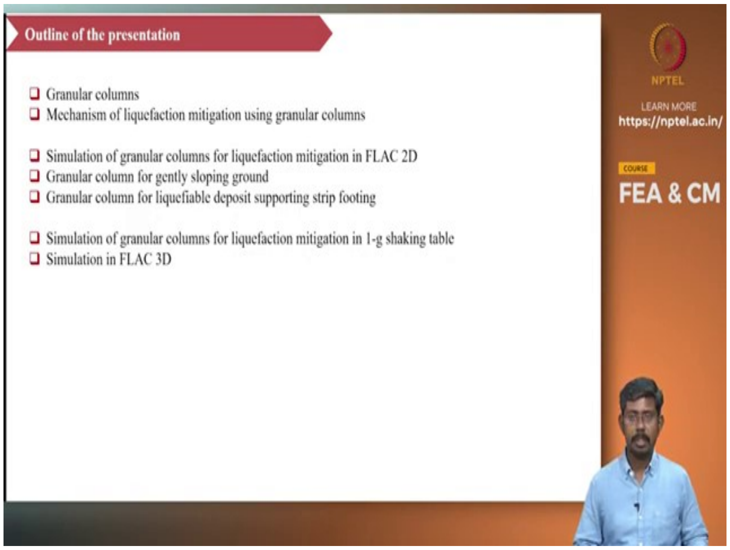

Outline of the presentation

- ☐ Granular columns
- ☐ Mechanism of liquefaction mitigation using granular columns
- ☐ Simulation of granular columns for liquefaction mitigation in FLAC 2D
- ☐ Granular column for gently sloping ground
- ☐ Granular column for liquefiable deposit supporting strip footing
- ☐ Simulation of granular columns for liquefaction mitigation in 1-g shaking table
- ☐ Simulation in FLAC 3D

The outline of the presentation is granular columns, a brief intro about granular columns and mainly the mechanism that are associated with granular columns which helps to mitigate the liquefaction. And the simulation of granular columns is illustrated using FLAC 2D and granular column for applications such as sloping ground and first strip footing is to be delivered here.

And the simulation we just performed on 1-g shaking table and as well as the simulations that was performed using FLAC 3D is to be demonstrated here.

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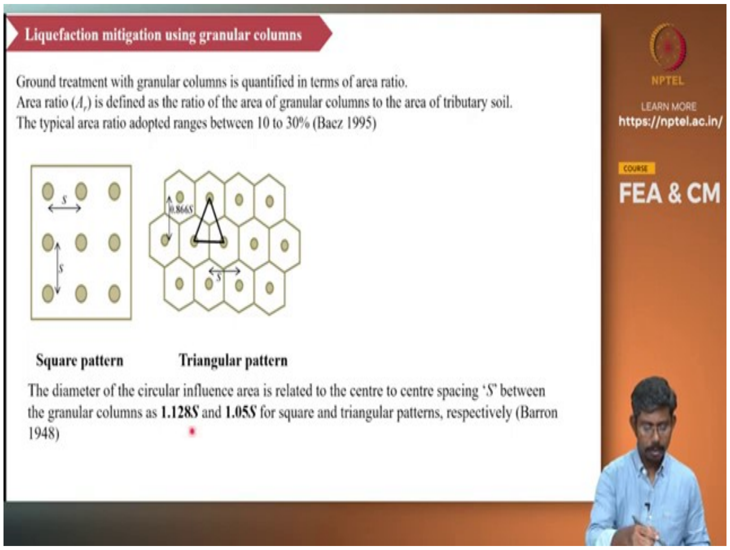

Liquefaction mitigation using granular columns

Ground treatment with granular columns is quantified in terms of area ratio.

Area ratio (A_r) is defined as the ratio of the area of granular columns to the area of tributary soil.

The typical area ratio adopted ranges between 10 to 30% (Baez 1995)

Square pattern **Triangular pattern**

The diameter of the circular influence area is related to the centre to centre spacing 'S' between the granular columns as **1.128S** and **1.05S** for square and triangular patterns, respectively (Barron 1948)

Firstly, granular columns for liquefaction mitigation, so, granular columns is nothing but the stone columns. The terminologies are used interchangeably. The treatment is defined in terms of area ratio. The extent of treatment is usually quantified in terms of area ratio, a term which is defined as area of granular columns. The term which is defined as area of the term area ratio is defined as the ratio of area of granular columns to that of the tributary soil.

The typical area ratio adapted for granular column treatment area ratio is defined as the ratio of area of granular columns to that of the surrounding soil, the tributary soil. So, usually the granular columns are installed either in a square pattern or in a equilateral triangular pattern. So, the typical area ratio ranges between 10 to 30 percent, so, the columns can be seen here. This is of circular shape and the intermediate region is made of the native soil and into which the columns are installed.

So that I am in the efficiency of the columns depends on the influence area of these columns. So, it depends on the diameter of the columns, as well as the spacing. So, here the effective diameter of the square pattern columns is 1.128S and for triangular pattern it is 1.05S, S is the spacing between the columns.

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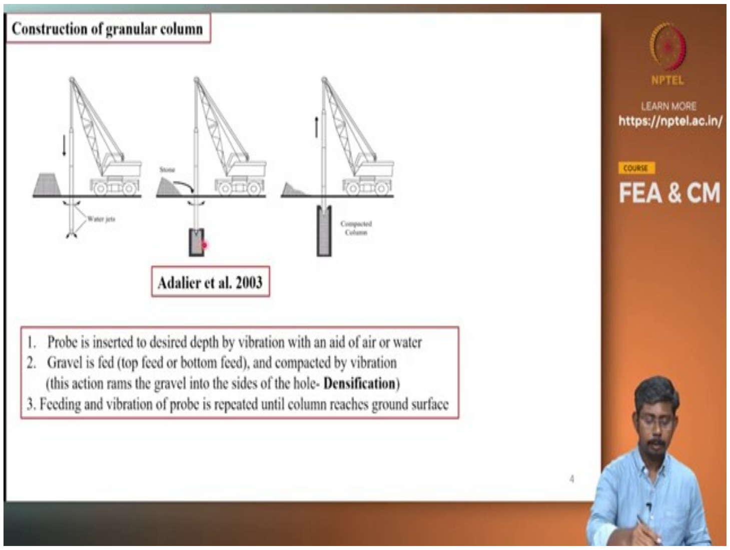

Construction of granular column

Adalier et al. 2003

1. Probe is inserted to desired depth by vibration with an aid of air or water
2. Gravel is fed (top feed or bottom feed), and compacted by vibration (this action rams the gravel into the sides of the hole- **Densification**)
3. Feeding and vibration of probe is repeated until column reaches ground surface

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Construction of granular columns so, this is usually carried out using a vibratory method. A vibratory probe is inserted into the ground and the probe is assisted by the water jets to soften the soil. And as they were, probe is vibrated the soil gets densified and once the probe reaches the desired depth, the material which is gravel will be fed from the top or from the bottom so that governs the top feed or bottom feed method.

When feeding the gravel into the through the probe, the probe will also be used to compact the gravel. So, by radially expanding the columns and densifying the surrounding soil. So, through this means the surrounding soil will get densified. So, it can be seen here, the stone the gravels are filled and the progressively the column is built and here almost the column reaches the ground surface.

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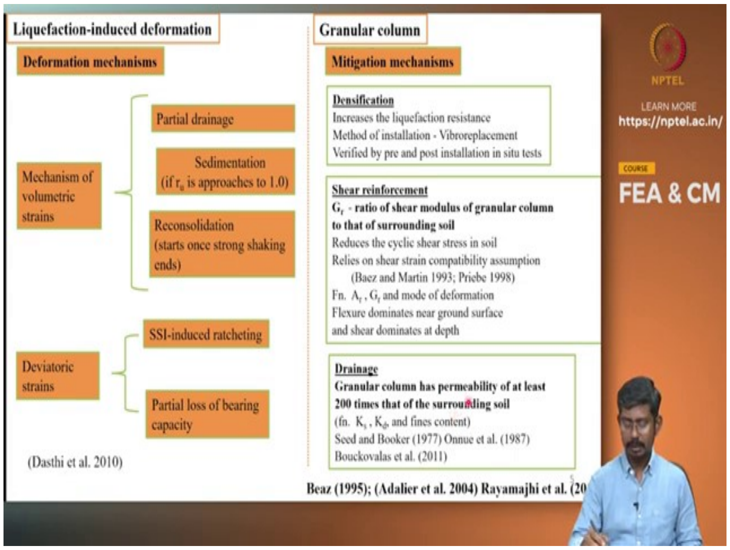

Liquefaction-induced deformation

Deformation mechanisms

Mechanism of volumetric strains
- Partial drainage
- Sedimentation (if r_u is approaches to 1.0)
- Reconsolidation (starts once strong shaking ends)

Deviatoric strains
- SSI-induced ratcheting
- Partial loss of bearing capacity

(Dasthi et al. 2010)

Granular column

Mitigation mechanisms

Densification
Increases the liquefaction resistance
Method of installation - Vibroreplacement
Verified by pre and post installation in situ tests

Shear reinforcement
G_r - ratio of shear modulus of granular column to that of surrounding soil
Reduces the cyclic shear stress in soil
Relies on shear strain compatibility assumption
(Baez and Martin 1993; Priebe 1998)
Fn. A_r , G_r and mode of deformation
Flexure dominates near ground surface
and shear dominates at depth

Drainage
Granular column has permeability of at least 200 times that of the surrounding soil
(fn. K_s , K_g, and fines content)
Seed and Booker (1977) Onnue et al. (1987)
Bouckovalas et al. (2011)

Beaz (1995); (Adalier et al. 2004) Rayamajhi et al. (20

So, it is important to note the deformation mechanisms that are caused by the it is important to note the deformation mechanisms of liquefaction. So, there are two types of which the first one is of volumetric strains. So, in case of volumetric strains, the three cases that contributes to the volumetric strain are partial drainage, sedimentation and reconsolidation. Partial drainage is the dissipation of excess pore water pressure that happens during the cyclic loading or during the earthquake loading.

Because the sand has got some permeability. So, as a result of which some excess pore water pressure will get dissipated even during the shaking. That is about partial drainage. The sedimentation is the one which has a predominant effect in case of the level ground deposits where, when the soil deposit reaches initial liquefaction that is r u approaches 1. So, it is almost will be in a fluidized state and the soil particle will sediment.

So, the result of which should be a huge volumetric strain in terms of which is the result of sedimentation is a excessive settlement. And the reconsolidation is whatever the dissipation of excess pore water pressure and the volumetric stain due to reconsolidation is due to the dissipation of excess pore water pressure that occurs after the shaking ends. Coming to the other type of deformation that is due to the deviatoric strains.

This occurs during the presence of a structure when a ground supports a structure there would be an effect of seismic soil structure interaction. And there will also be a bearing capacity issue. Coming to the mitigation mechanisms that are associated with granular columns.

Firstly, the densification, so, we saw that the installation of granular column will result in densification of surrounding soil.

So, the loose sand is more vulnerable to liquefaction so, when it gets densified. So, obviously the cyclic resistance of sand increases. So, in turn the liquefaction resistance increases. So, in case of sand, it can be densified through the vibratory means and this can be verified through the in situ tests. Before the treatment and after the treatment say for instance, if the SPD test is conducted, the effect of densification will get reflected in terms of n value.

And the other imported mechanism is shear reinforcement. So, this occurs because of the difference in the shear modulus between the shear enforcement effect arises as result of the difference in the shear modulus. The shear reinforcement effect arises due to the result of differences in the shear reinforcement effect arises as a result of the difference in the shear modulus between the granular column and the surrounding soil.

Obviously, the column is stiffer than the surrounding soil and this in turn leads to reduction in cyclic shear stresses that are experienced by the soil. And this particular mechanism shear reinforcement, the underlying assumption is the strain compatibility. So, the column is expected to deform in pure shear. So, thereby attracting more the effect induced cyclic shear stresses since the column attracts more shear stresses.

So, in turn, the stresses will that are experienced by the soil will be lower. So that is the aspect of this shear reinforcement, so, it is governed by the ratio G r that is the ratio of shear modulus of granular column to that of surrounding soil. A value of between 7 to 10 is necessary to obtain a substantial reduction in the shear stresses that are experienced by the soil in order to have a good shear enforcement effect.

So, this is governed by the area ratio and the G r shear modulus ratio and this G r governs the mode of deformation of the column. So, if flexure is present, if the column bends, so, obviously the effect of shear enforcement will reduce. Then the third mechanism that occurs as a result of stone column is the drainage. The column is known to have higher permeability than the soil.

So, normally the column is expected to have a two order of permeability to be higher than the surrounding soil. So, it is a function of K s the permeability of soil K d permeability of the granular column and the fines content. So, the fines content has a significant effect on the drainage capacity. As the fines could clog the drain, the clogging would reduce the drainage capacity.

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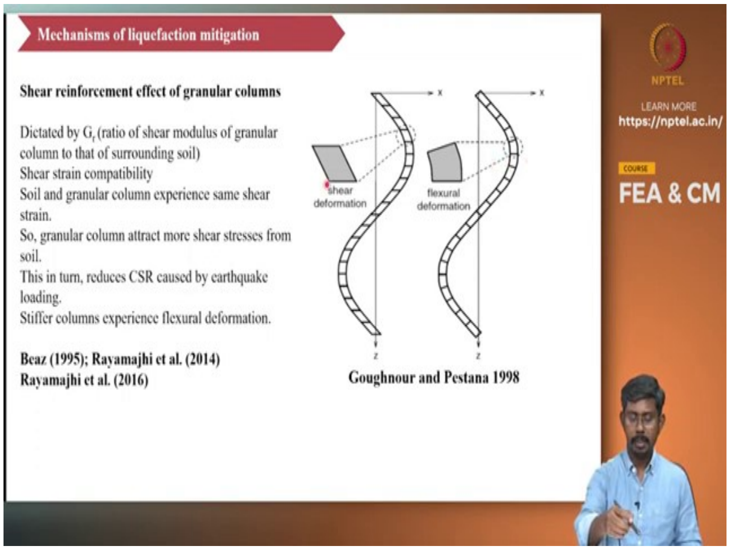

Mechanisms of liquefaction mitigation

Shear reinforcement effect of granular columns

Dictated by G_r (ratio of shear modulus of granular column to that of surrounding soil)
Shear strain compatibility
Soil and granular column experience same shear strain.
So, granular column attract more shear stresses from soil.
This in turn, reduces CSR caused by earthquake loading.
Stiffer columns experience flexural deformation.

Beaz (1995); Rayamajhi et al. (2014)
Rayamajhi et al. (2016)

Goughnour and Pestana 1998

Focusing on the shear reinforcement effect it is dictated by the shear modulus ratio and the assumption is shear strain compatibility and that is which means that the soil and granular column experiences the same shear strain. So, the granular column attract more stresses from when compared to the soil. So, this in turn reduces the cyclic stress ratio which is the cyclic chest stresses that are induced in soil due to earthquake loading.

And if the column is very stiff, so then it might experience the flexural deformation as opposed to the expected shear deformation. So, such cases are also reported by the research, several researches. So, it can be seen the columns certain region of the column experiencing shear mode of deformation and flexural mode of deformation. So, the shear reinforcement effect would be better when the soil experiences shear deformation but it would be very low when it experiences the flexural deformation.

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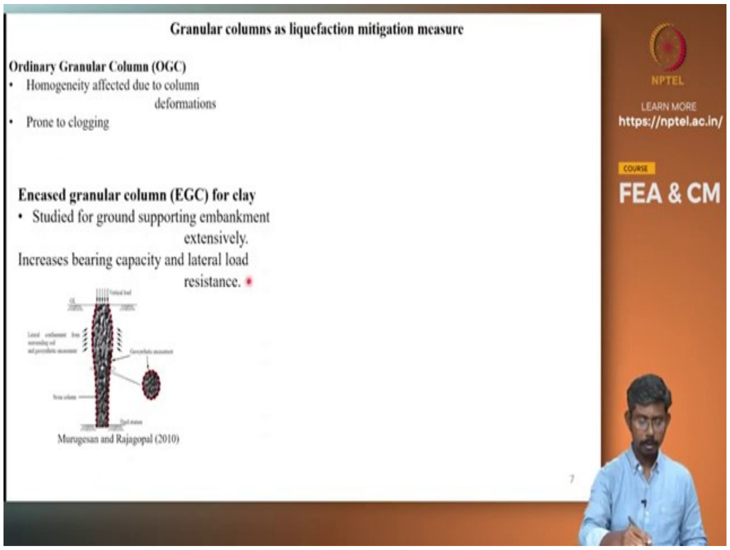
Granular columns as liquefaction mitigation measure

Ordinary Granular Column (OGC)
- Homogeneity affected due to column deformations
- Prone to clogging

Encased granular column (EGC) for clay
- Studied for ground supporting embankment extensively.

Increases bearing capacity and lateral load resistance.

Murugesan and Rajagopal (2010)

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Here comes the other term ordinary granular columns. The term ordinary here refers to the columns that does not have any geosynthetic encasement. So, the homogeneity of such columns are affected by the deformation of the soil and the fines content that are present in the native soil could possibly clog the drain which would reduce the drainage capacity of granular columns.

So, these two are the disadvantages of ordinary granular column. The other possibility is the encased granular column, so, the encased granular column is very popular in clay. Here you can see the column, it is wrapped with geosynthetic encasement. So, in case of clay softly deposit, it is known to increase the bearing capacity and lateral road assistance and it has been reported by several researchers in the past.

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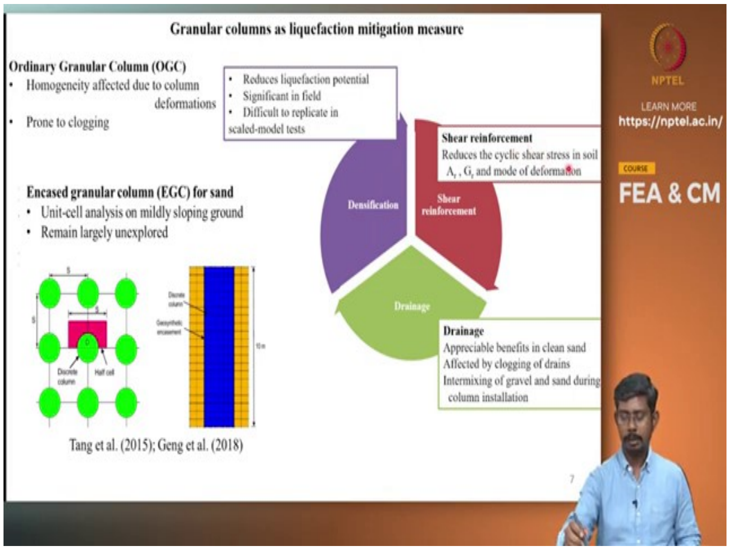
Granular columns as liquefaction mitigation measure

Ordinary Granular Column (OGC)
- Homogeneity affected due to column deformations
- Prone to clogging

- Reduces liquefaction potential
- Significant in field
- Difficult to replicate in scaled-model tests

Shear reinforcement
Reduces the cyclic shear stress in soil
A_r, G_r and mode of deformation

Encased granular column (EGC) for sand
- Unit-cell analysis on mildly sloping ground
- Remain largely unexplored

Drainage
Appreciable benefits in clean sand
Affected by clogging of drains
Intermixing of gravel and sand during column installation

Tang et al. (2015); Geng et al. (2018)

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When it comes to the use of encased granular column in sand for mitigating liquefaction. So, it is the data is very limited and most cases, the unit cell simulations are conducted to evaluate the response of encased granular column, really due to the ordinary granular columns. So, having the three mechanisms of liquefaction mitigation that are key to the performance of granular column this densification.

So, it reduces the liquefaction potential that is it increases the relative density of sand and it can be achieved in field as a result of installation of stone column. And this could not be easily replicated in the laboratory tests that are undertaken as a model. And shear reinforcement effect that this occurs as a result of the difference in the shear modulus between the two materials and the drainage. As a result of difference in the permeability.

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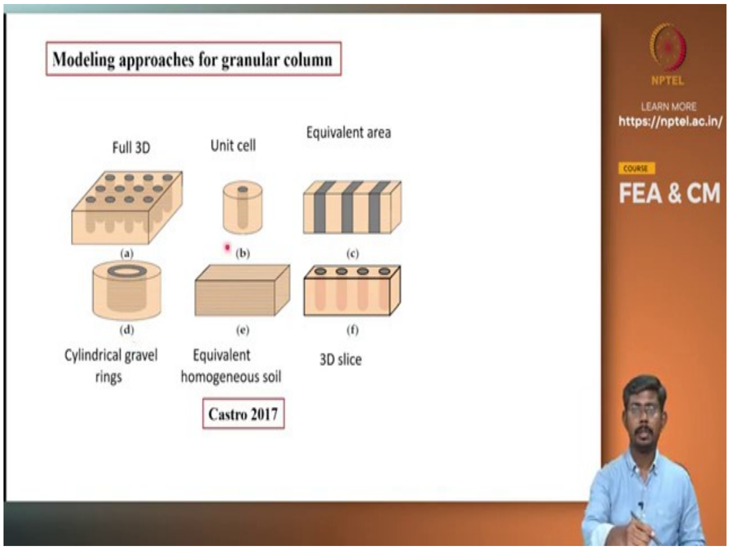

Modeling approaches for granular column

Castro 2017

For modelling, so, the computational effort is the para is the factor that governs the choice of modelling among the cases. The choices that are shown here, full 3D requires a significant computational effort and unit cell is a smaller model. It can be simulated with the reasonable computational effort and it is possible to model in both 2D as a axis symmetric problem and in full scale 3D as well equivalent area.

In this case, the 2D modeling is possible and the 3D slice then equal and homogeneous soil and the cylindrical gravel rings. So, this the choice of this approach could be vary with the, so, the choice of the approach depends upon the complexity of the problem and the computational resources that are available.

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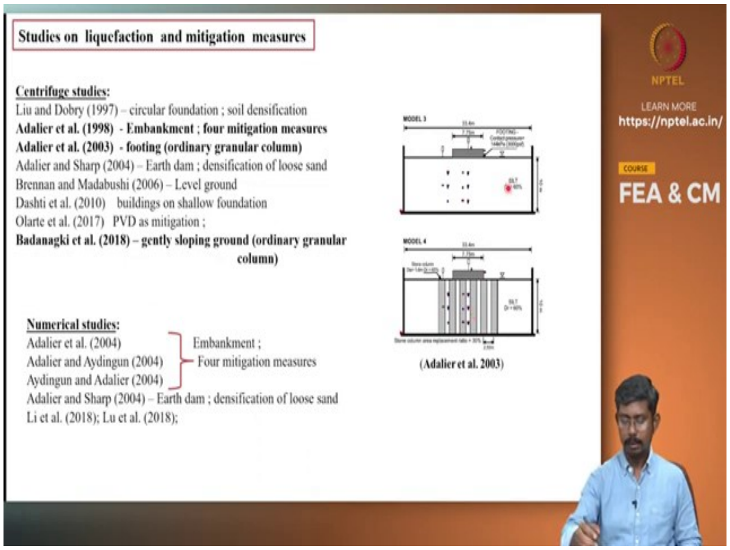

Studies on liquefaction and mitigation measures

Centrifuge studies:

Liu and Dobry (1997) – circular foundation ; soil densification

Adalier et al. (1998) - Embankment ; four mitigation measures

Adalier et al. (2003) - footing (ordinary granular column)

Adalier and Sharp (2004) – Earth dam ; densification of loose sand

Brennan and Madabushi (2006) – Level ground

Dashti et al. (2010) buildings on shallow foundation

Olarte et al. (2017) PVD as mitigation ;

Badanagki et al. (2018) – gently sloping ground (ordinary granular column)

Numerical studies:

Adalier et al. (2004), Adalier and Aydingun (2004), Aydingun and Adalier (2004) – Embankment ; Four mitigation measures

Adalier and Sharp (2004) – Earth dam ; densification of loose sand

Li et al. (2018); Lu et al. (2018);

(Adalier et al. 2003)

So, the previous studies have considered various mitigation mechanisms, the previous studies have considered different mitigation measures. And among them it is the granular column is very limited for instance, earlier at all 2003 considered soil deposit which is made of silt that supports the footing. So, here, in this case, the soil is treated with granular columns of area ratio that is 30 percent and the performance of the treated ground is explode and it is compared to the results from the untreated ground.

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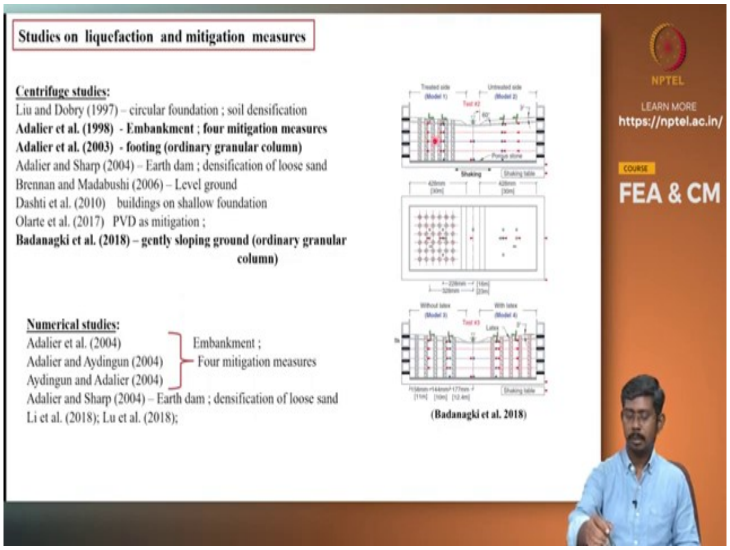

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Numerical studies:

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Adalier and Sharp (2004) – Earth dam ; densification of loose sand

Li et al. (2018); Lu et al. (2018);

(Badanagki et al. 2018)

And in the other case it can be seen the sloping ground is considered as a structure. In the other case, it can be seen that the sloping ground is considered and the granular column is used to treat the gentle slope. And here it is the untreated ground on the right hand side and the treated ground on the left side. It is the centrifuge model. The study was undertaken by Badanagki et al., 2018.

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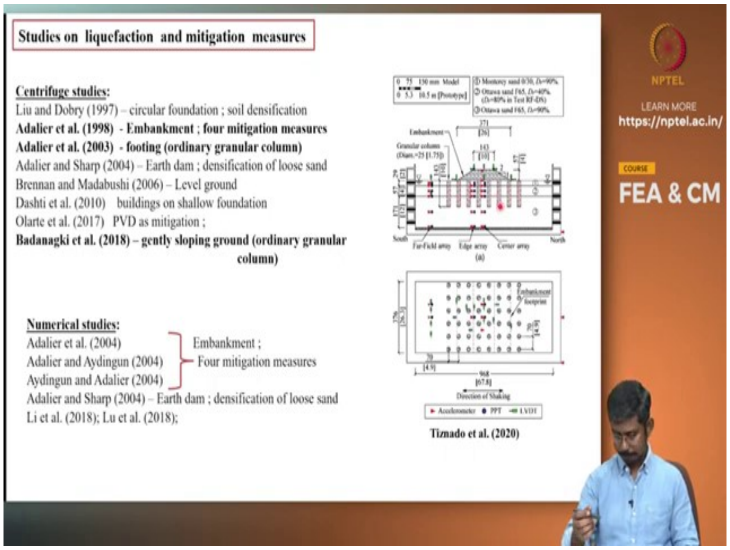

Studies on liquefaction and mitigation measures

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Numerical studies:

Adalier et al. (2004), Adalier and Aydingun (2004), Aydingun and Adalier (2004) – Embankment ; Four mitigation measures

Adalier and Sharp (2004) – Earth dam ; densification of loose sand

Li et al. (2018); Lu et al. (2018);

Tiznado et al. (2020)

And very recently, Tisnado considered an embankment with the foundation soil that is treated with the ordinary granular columns.

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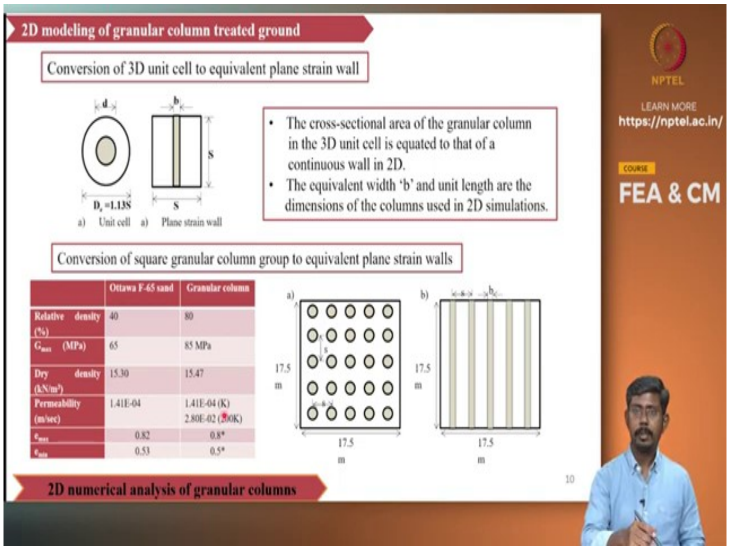

2D modeling of granular column treated ground

Conversion of 3D unit cell to equivalent plane strain wall

- The cross-sectional area of the granular column in the 3D unit cell is equated to that of a continuous wall in 2D.
- The equivalent width 'b' and unit length are the dimensions of the columns used in 2D simulations.

Conversion of square granular column group to equivalent plane strain walls

	Ottawa F-65 sand	Granular column
Relative density (%)	40	80
G_{max} (MPa)	65	85 MPa
Dry density (kN/m³)	15.30	15.47
Permeability (m/sec)	1.41E-04	1.41E-04 (K) 2.80E-02 (200K)
e_{max}	0.82	0.8*
e_{min}	0.53	0.5*

2D numerical analysis of granular columns

So, coming to the simulation of granular columns. So now, it is for a 2D model that is developed in FLAC. Here the granular column is modelled as a equivalent plane strain wall. So, the circular column is converted into a plane strain wall on the basis of equivalent area. So, it can be seen here, the circular column and the equivalent planes to involve. So, in case of the full scale treatment.

So, this would be the configuration of the width of the column and the spacing between the columns. So, here the soil deposit is made of whatever sand for the numerical model that is to be discussed and the granular column. So, both are modelled using PM4 sand and the basic properties are listed here. And here it can be noted the difference in the permeability considered for granular columns here K and 200K.

So, K refers to the case where the permeability of the soil is same as that of granular column. But in case of 200K, the permeability of the granular column is two orders higher than that of the surrounding soil. So, this is this difference is mainly considered to account for the drainage that occurs through the granular columns,

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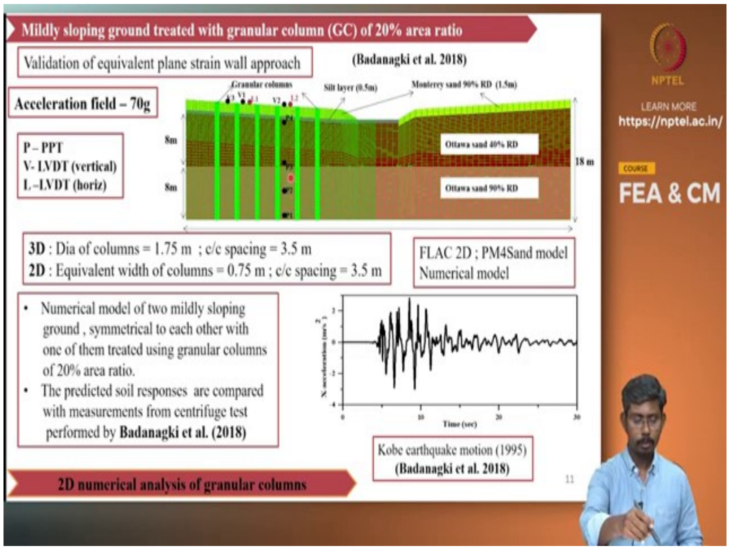

Mildly sloping ground treated with granular column (GC) of 20% area ratio

Validation of equivalent plane strain wall approach

(Badanagki et al. 2018)

Acceleration field – 70g

P – PPT
V- LVDT (vertical)
L –LVDT (horiz)

3D : Dia of columns = 1.75 m ; c/c spacing = 3.5 m
2D : Equivalent width of columns = 0.75 m ; c/c spacing = 3.5 m

FLAC 2D ; PM4Sand model
Numerical model

- Numerical model of two mildly sloping ground , symmetrical to each other with one of them treated using granular columns of 20% area ratio.
- The predicted soil responses are compared with measurements from centrifuge test performed by **Badanagki et al. (2018)**

Kobe earthquake motion (1995)
(Badanagki et al. 2018)

2D numerical analysis of granular columns

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So, this plane strain modelling approach is used to simulate a boundary value problem. This is originally a centrifuge experiment reported by Badanagki et al., 2018. So, wherein it considered the sloping ground so, the left hand side it is treated with granular columns of area ratio 20 percent. And the right side it is the untreated ground. It is indeed a layered soil profile.

The top layer is made of a dense sand and it is underlined by a silt low permeability silt and then the thicker layer is made of loose Ottawa sand and then the bottom layer is made of dense Ottawa sand. So, the 3D geometry is converted into equivalent to D can be seen actually, the columns are of 1.75 metre diameter and the equivalent width of the column for 2D model is 0.75 metre.

And the spacing is kept same because it is just the area is equated area of column. And the input motion that is used is Kobe motion to simulate the earthquake loading and here it can be seen the location of the instrumented locations, where the P refers to pore pressure. Transducers and V corresponds to the settlement and L corresponds to the lateral deformation of soil.

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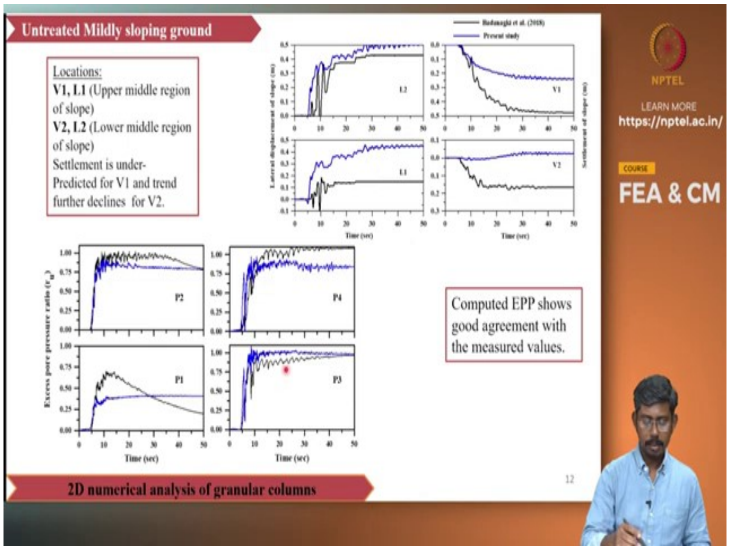

Untreated Mildly sloping ground

Locations:
V1, L1 (Upper middle region of slope)
V2, L2 (Lower middle region of slope)
Settlement is under-Predicted for V1 and trend further declines for V2.

Computed EPP shows good agreement with the measured values.

2D numerical analysis of granular columns

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First, for the untreated case, the responses are plotted here, so, it can be seen that the lateral deformations it shows a reasonable match, whereas the predicted the computed settlements, V1 and V2 are under predicted when compared to that of the measurements that are made from the centrifuge test. So, this is mainly attributed to the limitation associated with the numerical model.

Because it could not similarly, the sedimentation that occurs as a result of soil liquefaction. When it comes to the pore water pressure, a reasonably good match is achieved between the computed, excess pore pressures. And the measured excess pore pressure at most locations.

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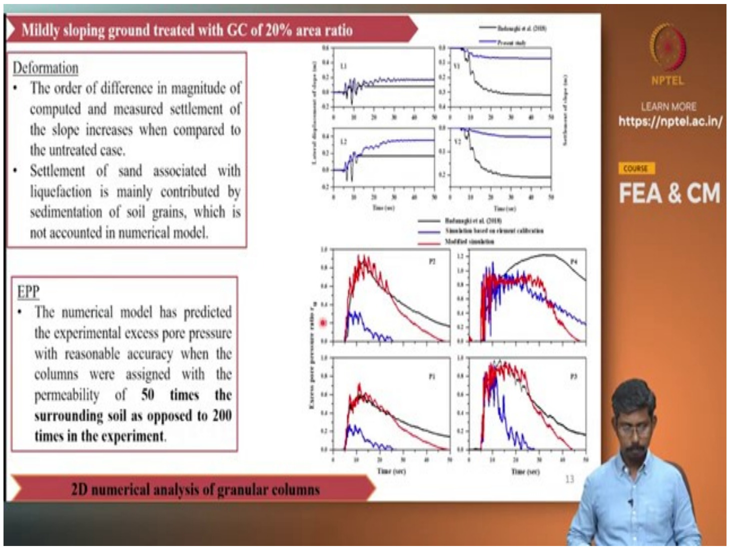

Mildly sloping ground treated with GC of 20% area ratio

Deformation

- The order of difference in magnitude of computed and measured settlement of the slope increases when compared to the untreated case.
- Settlement of sand associated with liquefaction is mainly contributed by sedimentation of soil grains, which is not accounted in numerical model.

EPP

- The numerical model has predicted the experimental excess pore pressure with reasonable accuracy when the columns were assigned with the permeability of **50 times the surrounding soil as opposed to 200 times in the experiment.**

2D numerical analysis of granular columns

When it comes to the treated ground, so, the similar case, the similar discrepancy is spotted in case of treated ground as well that is the under prediction of the settlements. And here the pore pressures are also affected here. The simulation of unlike the untreated ground here, the discrepancy is spotted in excess pore pressure as well. So, the simulation based on element calibration that is the parameters to represent the model parameters to represent the Ottawa sand.

That is obtained through the element calibration. That is represented by the blue coloured plots. You can see here the excess pore water pressures are very much under predicted. So, it corresponds to the permeability that is the actual the experimental case wherein the granular columns is 200 times more permeable than the surrounding soil. So, for this, the permeability of the granular columns is reduced to 50 times instead of 200 times.

So that is denoted as modified simulation. So, which offers a much better prediction when compared to that of the predictions that are made using the element calibrated data.

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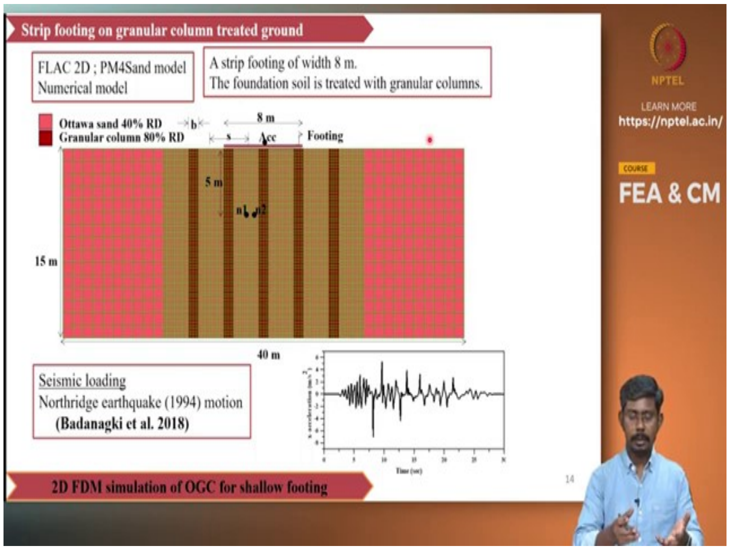

Strip footing on granular column treated ground

FLAC 2D ; PM4Sand model
Numerical model

A strip footing of width 8 m.
The foundation soil is treated with granular columns.

Seismic loading
Northridge earthquake (1994) motion
(Badanagki et al. 2018)

2D FDM simulation of OGC for shallow footing

Following the sloping ground, a footing is considered a strip footing is considered to rest on a liquefiable deposit of 15 metre thick and here the granular columns are used here to treat the liquefiable deposit. The same numerical methodology is adapted over here. The numerical model comes from FLAC 2D and PM4Sand model. It is the constitute model used to represent the strain behaviour of sand, as well as granular column during the cyclic loading.

The width of the footing turns to be 8 metre and these seismic loading is simulated through the Northridge earthquake motion that is applied at the base of the numerical model and as far as boundary condition is considered. The boundaries are the left boundary and right boundaries are fixed in the horizontal direction but they are free in the vertical direction to allow the settlement.

That is the mechanical boundary condition when it comes to the fluid boundary condition. The lateral sides and the bottom is impermeable. The top the pore water pressure is allowed to escape and this is the coupled stress flow analysis where in each time step the excess pore water pressure is generated as a result of the volumetric contractive behaviour that is experienced by the sand and on the other hand.

The dissipation of excess pore water pressure is also accounted. So, the recipient which happens as a result of the permeability of the soil in case of untreated ground. In case of treated ground the dissipation would be enhanced by the presence of the granular column. So, these aspects are inherent in the numerical model. So, it was discussed in the previous lecture as well.

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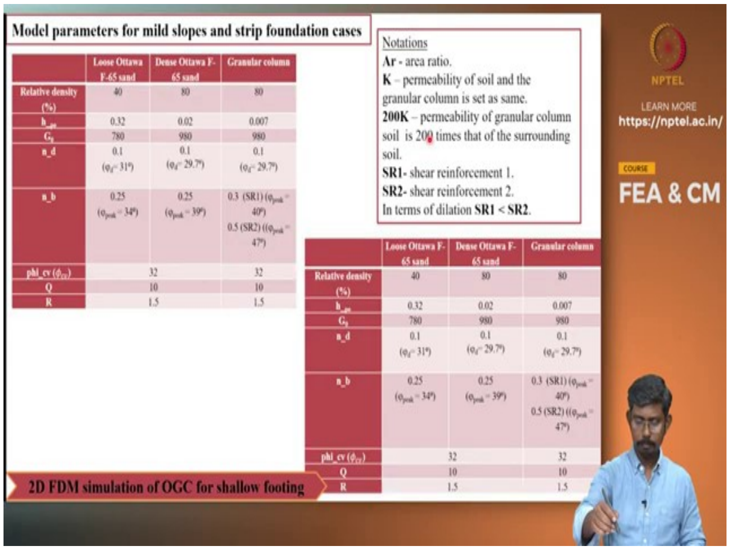

Model parameters for mild slopes and strip foundation cases

	Loose Ottawa F-65 sand	Dense Ottawa F-65 sand	Granular column
Relative density (%)	40	80	80
h_{po}	0.32	0.02	0.007
G_0	780	980	980
n_d	0.1 (φ_d = 31°)	0.1 (φ_d = 29.7°)	0.1 (φ_d = 29.7°)
n_b	0.25 (φ_{peak} = 34°)	0.25 (φ_{peak} = 39°)	0.3 (SR1) (φ_{peak} = 40°) 0.5 (SR2) ((φ_{peak} = 47°)
phi_cv (ϕ_{cv})	32		32
Q	10		10
R	1.5		1.5

Notations

Ar - area ratio.

K – permeability of soil and the granular column is set as same.

200K – permeability of granular column soil is 200 times that of the surrounding soil.

SR1- shear reinforcement 1.

SR2- shear reinforcement 2.

In terms of dilation **SR1 < SR2**.

	Loose Ottawa F-65 sand	Dense Ottawa F-65 sand	Granular column
Relative density (%)	40	80	80
h_{po}	0.32	0.02	0.007
G_0	780	980	980
n_d	0.1 (φ_d = 31°)	0.1 (φ_d = 29.7°)	0.1 (φ_d = 29.7°)
n_b	0.25 (φ_{peak} = 34°)	0.25 (φ_{peak} = 39°)	0.3 (SR1) (φ_{peak} = 40°) 0.5 (SR2) ((φ_{peak} = 47°)
phi_cv (ϕ_{cv})	32		32
Q	10		10
R	1.5		1.5

2D FDM simulation of OGC for shallow footing

So, these are the properties chosen the input parameters chosen for simulating the Ottawa sand granular column. So, the h p naught is the contraction rate parameter G naught is the that represents the elastic shear modulus, n_d the dilatency surface, n_b the bounding surface. So, phi series, the critical states of phase and Q and R are the empirical constants that are used to construct the critical state surface.

So, among these here two different cases of n_b is considered the bounding surface. So, the bounding surface represents the peak friction angle, so, 40 degrees and 47 degrees considered. This is to mainly explore the effect of shear reinforcement that the granular column offers. So, SR1 is the property more or less more or less similar to that of these are sand, dense sand, whereas SR2 is much higher when compared to SR1.

So, this is expected to bring out the difference that comes as a contribution from the shear reinforcement effect in terms of permeability. K and 200K as mentioned previously, K refers to the permeability that granular column and the surrounding soil has the same value. 200K is the granular column will have 200 times more permeability than the surrounding soil SR1 and SR2. It refers to the shear enforcement effect.

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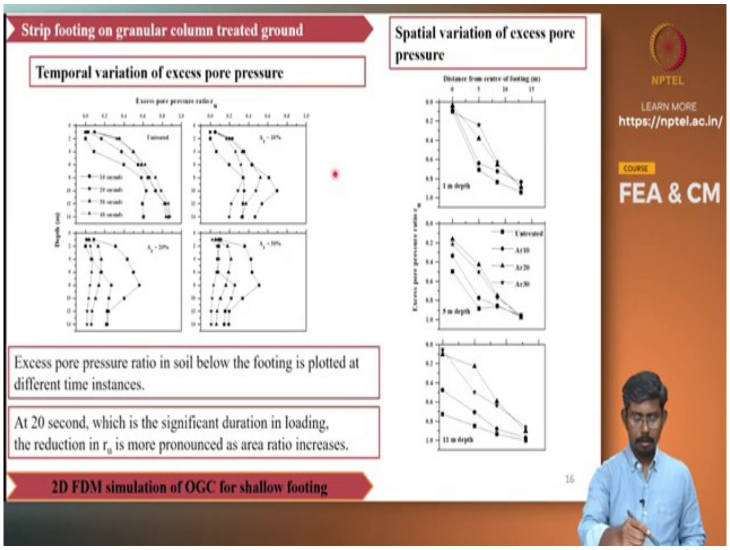

Strip footing on granular column treated ground

Temporal variation of excess pore pressure

Spatial variation of excess pore pressure

Excess pore pressure ratio in soil below the footing is plotted at different time instances.

At 20 second, which is the significant duration in loading, the reduction in r_u is more pronounced as area ratio increases.

2D FDM simulation of OGC for shallow footing

Coming to the computer responses in the 2D numerical model, the excess pore pressure plots are plotted here. The granular column treatment is undertaken for three different area ratios area ratio of 10 percent, area ratio of 20 percent and 30 percent. So, it can be seen that for untreated case, so, this particular plot corresponds to the temporal variation of excess pore water pressure.

That is at different times the pore water pressure is plotted and it can be seen that with the increase in the degree of treatment. So, the reduction in excess pore water pressure is quite obvious. So, it can be seen the progressive reduction in area ratio of 10 percent when compared to untreated and little lower in area ratio of 20 percent and compared to 10 percent. And finally, the 30 percent array ratio offers the least excess pore water pressure.

Among all these cases, so, this is the improvement that occurs as a result of the granular column treatment that is reflected in terms of excess pore water pressure in a temporal manner that is with respect to time. When it comes to the depth so, the spatial variation of excess pore water pressure. So, here at three different depths 1 metre depth from ground, 5 metre and 11 metre is plotted and it can be seen that for different area ratios the excess pore water pressure is.

It can be seen that for the spatial variation of excess pore water pressure that is here, it is with respect to depth. So, r u axis is plotted in vertical and this is the distance away from centre of the footing. So, this is basically for the soil below the centre of the footing and at depth 1 metre for each for every depth for each depths when it comes to the spatial variation of excess pore pressure.

So, the plots are made in terms of depth, so, 3 different depth are chosen, so, 1 metre, 5 metre and 11 metre. So, the x-axis corresponds to the distance from the centre of the footing and the y axis corresponds to the excess pore pressure ratio. So, at every depth it can be seen that the r u is quite higher for the untreated case and with increase in the treatment for area ratio of 10, 20 and 30. The excess pore pressure reduction is evident in this plots with respect to depth as well.

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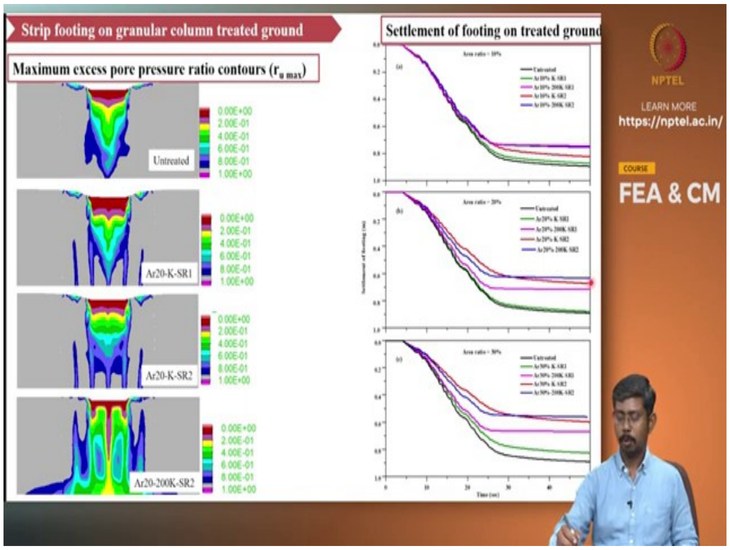

Strip footing on granular column treated ground

Maximum excess pore pressure ratio contours ($r_{u\,max}$)

Settlement of footing on treated ground

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So, the other means of expression in order to show additional insides through the excess pore pressure ratio. These plots correspond to different cases untreated and this is for area ratio of 20 percent, no additional drainage through granular columns and this is shear reinforcement and this is shear reinforcement 1. That is not much of shear enforcement effect is expected for this case.

And in this case shear enforcement effect will be there and in the last case the drainage is also included. So, it can be seen that with respect to the excess pore pressure ratio that is r u maximum value of excess pore pressure that I recorded during the cyclic loading. So, it can be seen for untreated. It is like the entire free field region. That is a region away from the footing is liquefied r u is about 1 and not much difference in case of shear reinforcement 1.

And it the improvement is still lags when compared to even in case of SR2 where the peak friction angle is set to 47 degree, as opposite to that of 40 degree in SR1. Still, it does not make much differences in terms of excess pore pressure ratio. But it when comes to the drainage when the drainage, through the granular columns is allowed it can be seen it is obvious that it is excess pore pressure plot.

It is indeed related to pore pressure ratio and the drainage. So, this manifests the effect of the shear reinforcement and the drainage on the pore pressure responses of the subsoil for the settlement of footing. It is plotted for 3 different area ratios 10 percent, 20 percent and 30 percent. So, it can be seen that the blue line that corresponds to the case where enhanced drainage is considered and the shear reinforcement effect is also in place.

So, in each of this case, so, this blue line case and even the interesting aspect is the red line is also not far from the blue line. So, in which case the drainage is not there but it is the shear reinforcement effect. So that also contributes for higher area ratios. So, though it may not be so, in all these three cases, it can be seen that for irrespective of area ratio. So, the shear reinforcement effect has a pronounced effect on the settlement of footing.

But the net reduction is not a substantial amount in terms of the settlement of footing in all these cases.

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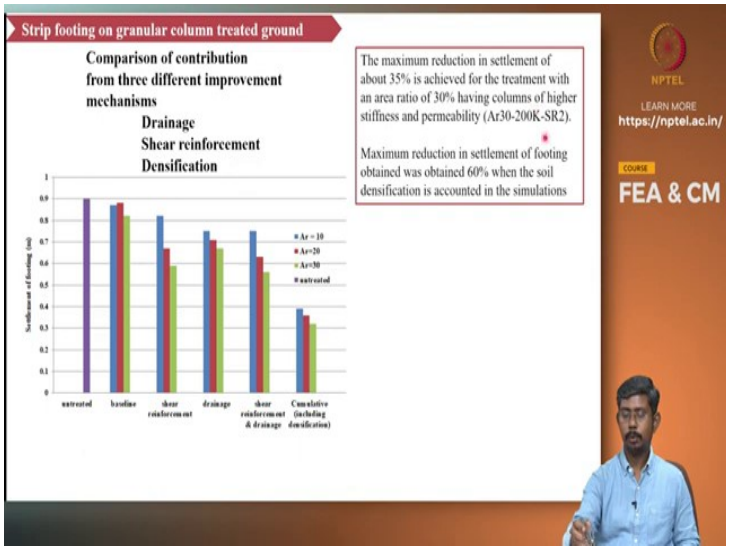

Strip footing on granular column treated ground

Comparison of contribution from three different improvement mechanisms

Drainage
Shear reinforcement
Densification

The maximum reduction in settlement of about 35% is achieved for the treatment with an area ratio of 30% having columns of higher stiffness and permeability (Ar30-200K-SR2).

Maximum reduction in settlement of footing obtained was obtained 60% when the soil densification is accounted in the simulations

So, far, only the drainage and shear reinforcement is considered. The densification was not considered so, when the densification is included, so, all together, the outcome becomes quite different. It can be seen so, for this baseline correction it is not much difference with respect to untreated case. So, this one corresponds to SR1 case. So, where the granular columns are all most like the dense sand in case of SR1, where granular columns have a higher stiffness.

So, the shear reinforcement effect is visible and that too, it is apparent with respect to the area ratio as well. So, for area ratio of 30 percent it is the least one among the shear investment effect. When it comes to drainage the effect of area ratio is not pronounced and when it comes to the combination of shear reinforcement and drainage effect. So, the difference that is obviously that is contributed by shear reinforcement as reflected here and once the densification is included.

That is, we know that the dense sand behaves much better and compared to loose sand because it is liquefaction resistance that is the cyclic shear resistance is high. So, the reduction significant reduction in the settlement of footing was observed. When the foundation soil is said to be densified. As a result of installation of stone columns. So, this even for a area ratio of 30 percent and when the full drainage is allowed, along with the shear reinforcement effect.

So, the maximum reduction in the settlement attitude was 35 percent when compared to that of untreated case. But when the densification of soil is included, the reduction in settlement that is obtained is 60 percent which is almost twice as that of what the other two mechanisms contributes. So, this highlights the influence or effectiveness of the densification.

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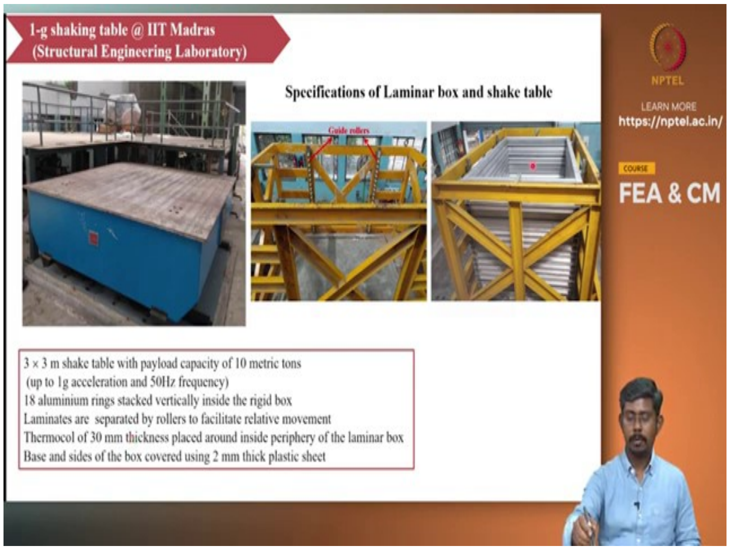

1-g shaking table @ IIT Madras
(Structural Engineering Laboratory)

Specifications of Laminar box and shake table

3 × 3 m shake table with payload capacity of 10 metric tons
(up to 1g acceleration and 50Hz frequency)
18 aluminium rings stacked vertically inside the rigid box
Laminates are separated by rollers to facilitate relative movement
Thermocol of 30 mm thickness placed around inside periphery of the laminar box
Base and sides of the box covered using 2 mm thick plastic sheet

Apart from the numerical simulations that was carried out using FLAC 2D and PM for sand as a soil constitute model. So, 1-g shaking table tests were conducted to evaluate the performance of the granular columns. So, this is the shaking table facility available at the structural engineering laboratory at IIT Madras. It is a 3 metre by 3 metre shaking table. So, can you handle it up to 1-g acceleration and 50 hertz frequency and the specifications of the and the rigid box is shown here.

It is fitted with grid rollers that aids the movement of the aluminum rings that is the laminar box. So, 18 aluminum rings are stacked to form the laminar box and these laminates are separated by the roller that is present in between them to facilitate the relative movement. And in the sides thermocol was placed and in the sides thermocol was used and the sides thermocol was placed along the interior periphery of the laminar container.

And the plastic sheet was used to cover the interior surfaces of the laminar box prior to the placement of the specimen that is the formation of the soil model.

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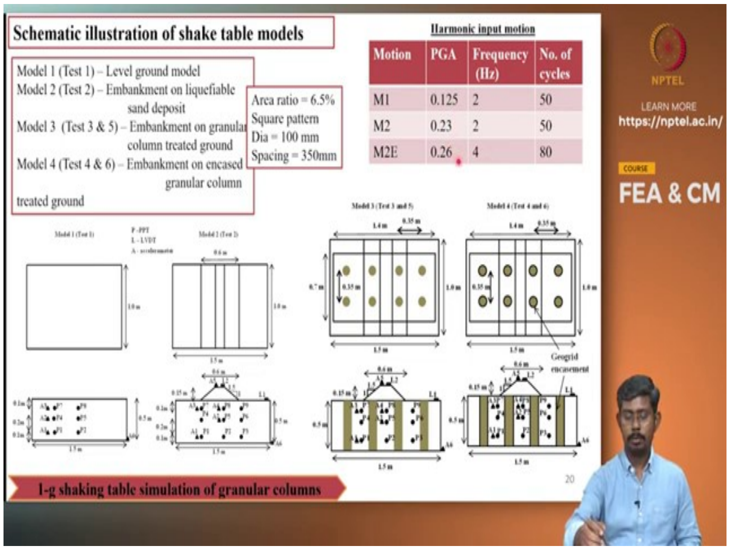

Schematic illustration of shake table models

Model 1 (Test 1) – Level ground model
Model 2 (Test 2) – Embankment on liquefiable sand deposit
Model 3 (Test 3 & 5) – Embankment on granular column treated ground
Model 4 (Test 4 & 6) – Embankment on encased granular column treated ground

Area ratio = 6.5%
Square pattern
Dia = 100 mm
Spacing = 350mm

Harmonic input motion

Motion	PGA	Frequency (Hz)	No. of cycles
M1	0.125	2	50
M2	0.23	2	50
M2E	0.26	4	80

1-g shaking table simulation of granular columns

So, totally four different models are considered and 6 shaking table tests are performed. So, the first test is a reference test that is just a level ground. And the second 1 forms a benchmark case where an embankment is placed on an untreated liquefiable sand opposite. And in model 3 the embankment is resting on a ground which is improved with the granular column ordinary granular column.

And then the 4th model is the embankment supported by the ground that is treated with encased granular column. So, here geogrid is used as an encasement. So, the area ratio considered was 6.5 percent and the square pattern was adopted the dia of column is 100 mm and the spacing between the columns is 350 mm. So, coming to the configuration of the test in plan. So, the first test is just a level ground and in the second case, an embankment is there.

Coming to the instrumentations these are pore pressure sensors p1 to p9 and A1 to A6 are the accelerometers. And the L1 and L2 is the displacement rest uses these are the instrumented locations, wherein the soil responses are tracked during the loading. Model 3 and model 4 so, model 3 comprises of ordinary granular columns and model 4 comprises of encased the granular columns that is the geogrid encased columns.

Coming to the loading here it is harmonic in nature and different PGA was used for motion 1 motion 2 and motion 2E.

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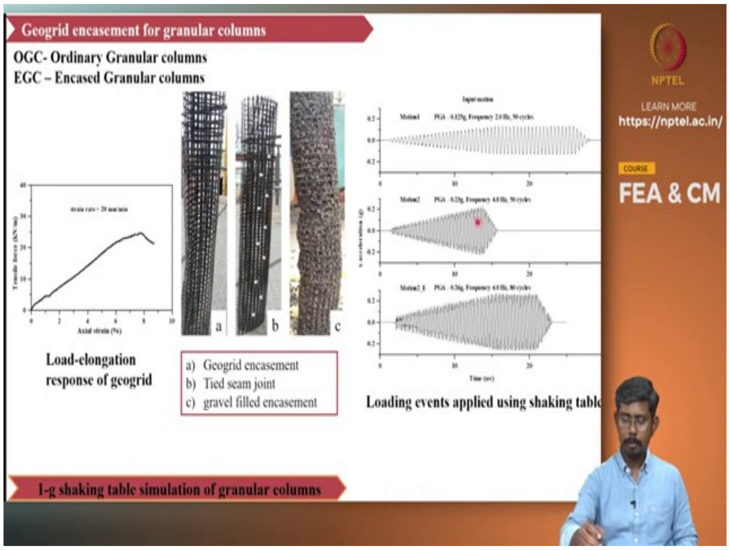

Geogrid encasement for granular columns

OGC- Ordinary Granular columns
EGC – Encased Granular columns

Load-elongation response of geogrid

a) Geogrid encasement
b) Tied seam joint
c) gravel filled encasement

Loading events applied using shaking table

1-g shaking table simulation of granular columns

So, this is the response of the geogrid to the wide, with tensile strength test, so, the load elongation response is plotted here. The train rate is 20 mm per minute. And here it can be seen the geogrid is shown here geogrid filled with the gravel can be seen here. And then the motions that a user do simulate the loading are motion 1, 2 and 2E can be seen. So, 0.125 G 0.23 G is a peak amplitude and 0.26 G for the third loading event.

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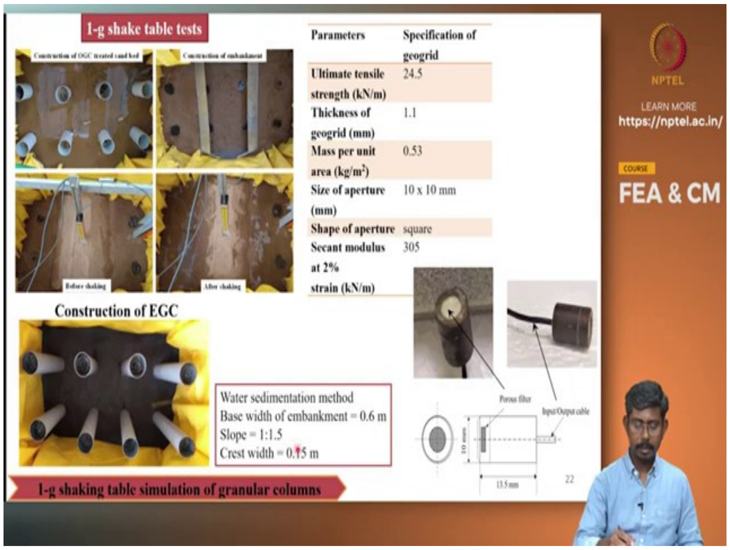

1-g shake table tests

Parameters	Specification of geogrid
Ultimate tensile strength (kN/m)	24.5
Thickness of geogrid (mm)	1.1
Mass per unit area (kg/m²)	0.53
Size of aperture (mm)	10 x 10 mm
Shape of aperture	square
Secant modulus at 2% strain (kN/m)	305

Construction of EGC

Water sedimentation method
Base width of embankment = 0.6 m
Slope = 1:1.5
Crest width = 0.15 m

1-g shaking table simulation of granular columns

The sequence of the formation of sand specimen is shown here. This is construction of ordinary granular column treated sand bed. Here the PVC pipes are placed prior to the pouring of sand and the gravel is filled inside it. Then water sedimentation is the method adapted to construct the specimen here. So, water is filled and the soil is fluidiated and the quantity of water required to saturate the sand is calculated in prior.

To the formation of quantity of water required to saturate the sand is calculated and the corresponding quantity of water is poured. And it is followed by the sand fluidiation to form the sand bed. And the mold is of desired size is used to form the embankment. Here the instrumentation can be seen here the heavy duty here and the accelerometer here and this is before the shaking event and this is after the shaking event.

It can be seen the embankment is still in place without much damage and it can be seen the excess pore here. It can be seen that the water that escaped through the granular columns is existing at the surface for the construction of encased granular columns. So, the encasement is placed within the PVC first and followed by filling of the gravels. And it is the same procedure that followed for the construction of ordinary granular columns is followed here as well.

The specifications of geogrid used are the ultimate tensile strength is 24.5 kilo Newton per metre. And it is thickness, is about 1.1 mm and the opening size is 10 mm by 10 mm and the second modulus is 3.5 kilo Newton per metre at a strain of 2 percent. And this is the pore pressure sensor that is used to measure the excess pore water pressure, this is a tiny sensor capable of measuring the pore water pressure up to 200 kPa.

The base width of embankment is 0.6 metre and the slope is 1.5 and the crust width is 0.15 metre.

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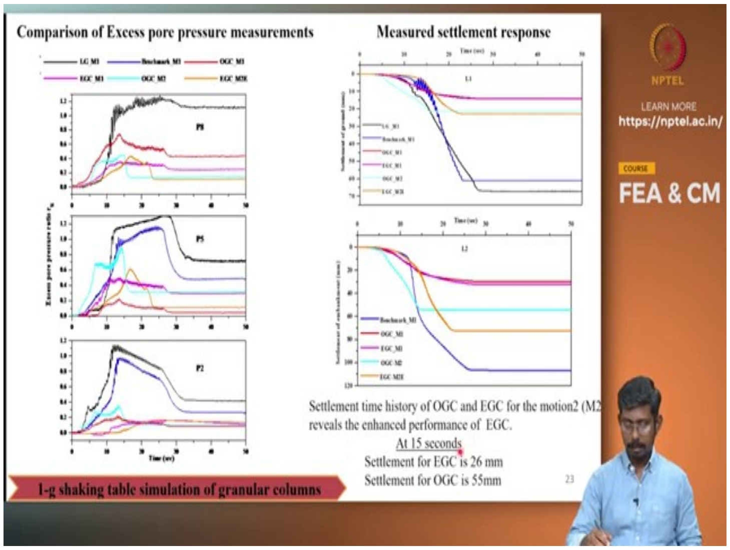

Comparison of Excess pore pressure measurements

Measured settlement response

Settlement time history of OGC and EGC for the motion2 (M2) reveals the enhanced performance of EGC.

At 15 seconds

Settlement for EGC is 26 mm

Settlement for OGC is 55mm

1-g shaking table simulation of granular columns

Firstly, the excess pore pressures here P4, P1 and P7. These locations correspond to the soil that lies below the toe of the embankment. So, here it can be seen that at various locations, so, here Benchmark model ordinary granular column for the first motion which is of lower intensity when compared to others. The second motion which is stronger and M2E and M2 are same in terms of almost same in terms of the magnitude.

But the number of loading cycles is higher over here in M2E. So, it can be seen here for this EGC M2E and OGC M2 will have a different trends when compared to the other ones. That is because of the difference in the intensity of loading. But overall, it can be seen that for the treated cases OGC and EGC there excess pore pressure ratio is lower. The excess power pressure for the treated cases OGC and EGC can be seen at locations P1 and P4.

The treated locations have indicated consistently lower excess pore pressure when compared to the untreated cases the black one corresponds to the level ground, the blue one corresponds to the benchmark model. That is the embankment resting on a untreated foundation soil The other locations, such as P2 P5 P8, corresponds to the soil the foundation soil that lies below the centre of the embankment.

So, similar trends can also be seen here, the untreated ones reaching more than one in some cases. And they treated once they are far lower and compared to the untreated cases. Coming to the settlement response this is L1 these are the far field and this L2 is the measure of settlement of embankment. So, here can be seen that the level ground has the maximum settlement followed by the benchmark model that is also untreated case.

And here the reason that the presence of embankment leads to the lateral displacement of soil foundation soil. So, it is because of which even here in fairfield, the settlement is lesser in case of the benchmark model and compared to the level ground case coming to the other treated cases. So, it can be seen that they are far lower when compared to the untreated case. And more importantly, the settlement of embankment can be seen here.

The settlement of OGC M1 and OGC M2 are compared to the settlement of the level ground. The settlement of embankment is a better indicator of the performance. So, here it can be seen OGC M1 and EGC M2. It can be seen that OGC M1 and EGC M1 there is almost no difference between these two cases. So because of which the intensity is increased from 0.125G in case of M12, 0.23 G to M2 case that is for OGC M2 and EGC M2 in order to distinguish the response of ordinary and encased granular columns.

So, in fact, encased granular columns, the number of loading cycles were increased from 50 to 80 in order to further have a better view of the performance. So, it is noted that the settlement of encased granular column is 26 mm for at 15 seconds. As a reference time or number of loading cycles that is OGC M2 that is, it has only 50 cycles. So, for the same 50 cycles. So, the OGC has 55 mm of settlement and EGC has a settlement of 26 mm.

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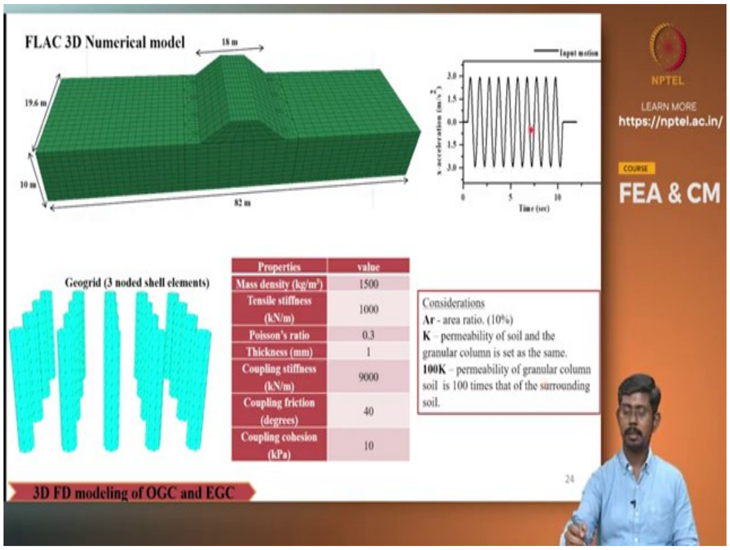

FLAC 3D Numerical model

Geogrid (3 noded shell elements)

Properties	value
Mass density (kg/m³)	1500
Tensile stiffness (kN/m)	1000
Poisson's ratio	0.3
Thickness (mm)	1
Coupling stiffness (kN/m)	9000
Coupling friction (degrees)	40
Coupling cohesion (kPa)	10

Considerations

Ar - area ratio. (10%)

K – permeability of soil and the granular column is set as the same.

100K – permeability of granular column soil is 100 times that of the surrounding soil.

3D FD modeling of OGC and EGC

Other than the shaking table test. So, a case study was considered using FLAC 3 numerical model, FLAC 3D numerical model. So, these are the dimensions, so, the width of foundations soil in x direction is 82 metre in y direction, is 19.6 metres and the embankment is of 18 metre wide and 4 metre height. This particular exercise is shown here to further interpret the response the effectiveness of in case granular columns.

So, the geogrid is used here that is model using the shell elements. So, these elements are capable of capturing the membrane responses. That is, it can take the tensile stresses the membrane stresses but not the bending. So, it can represent the shear interaction between the soil and the geogrid and this is a elastic material with no failure. So, the specifications of geogrid R here it is 1000 kilo Newton per metre is a tensor stiffness and the thickness is of 1 mm.

And these are the interface properties that is with respect to the soil for geogrid element. Area ratio of 10 percent is considered here and the permeability maximum permeability difference between the soil and granular column is made to be 100 times. This is to capture the drainage mechanism and the loading used here is an harmonic input motion of a 0.3G amplitude and 1 hertz frequency.

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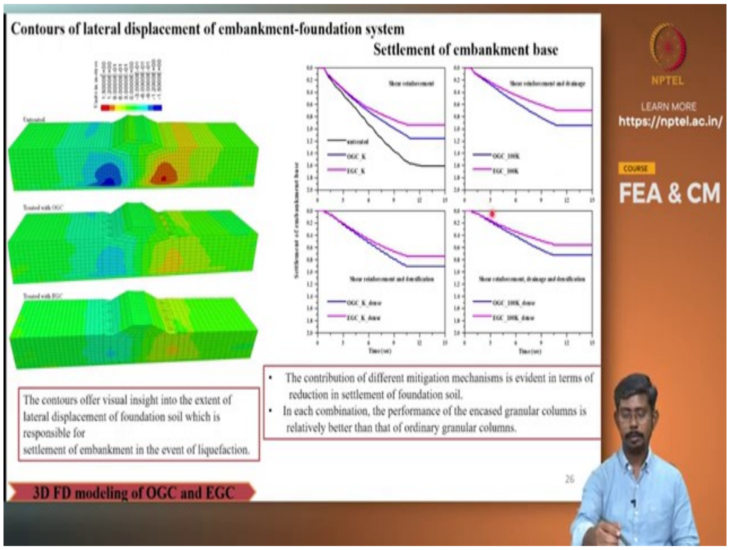

Contours of lateral displacement of embankment-foundation system

The contours offer visual insight into the extent of lateral displacement of foundation soil which is responsible for settlement of embankment in the event of liquefaction.

- The contribution of different mitigation mechanisms is evident in terms of reduction in settlement of foundation soil.
- In each combination, the performance of the encased granular columns is relatively better than that of ordinary granular columns.

3D FD modeling of OGC and EGC

So, here, NTUASAND model is used as a constitutive model to represent the soil behaviour. This is also a bounding surface model quite similar to the PM4 sand model. And NTUASAND model can capture the soil behaviour at low strain as well. So, for which this Ramberg was good non-linear historic formulation is introduced and as opposed to the PM4 sand model that the tiny yield surface that exists in the PM4 sand model is not present over here.

So that is what it is vanished, elastic region so that smaller yield surface is now reduced to a point. And similarly, the fabric tensor that is quite same as what it was discussed in the PM4 sand model. It is to account for the change in orientation of soil particles, like that occurs as a result of the dilation. So, NTUASAND model is used for both sand and gravel that is, for soil deposit as well as granular column.

It can be seen here with the lateral displacement contours for untreated ground. So, there is a significant lateral deformation of foundation, soil below the toe of embankment, whereas that for OGC is low and for EGC even better. So, this offers a visual insight for the performance of the ordinary and in case granular columns in terms of the settlement of foundation soil. So, it is plotted in terms of different combinations of the mitigation mechanisms.

So, it can be seen that the encased granular columns performs consistently better when compared to the ordinary granular columns.

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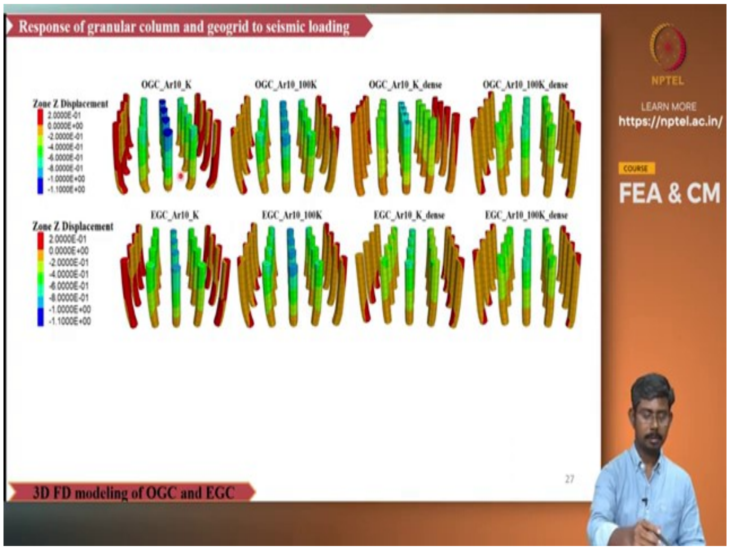

Response of granular column and geogrid to seismic loading

3D FD modeling of OGC and EGC

So, here the response of granular column is isolated. It is plotted separately, the Z displacement I mean the vertical settlement of the granular column. So, for ordinary granular columns without the drainage aspect, so, the settlement it can be seen the central columns are experiencing more settlements. But gradually this decreases when the drainage is introduced and further when densification is increased, I mean densification is considered.

And finally, all three mechanisms that is, the shear reinforcement which is inherent and here drainage, as well as densification. So, the columns behave much stiffer and compared to the first case. This is for ordinary granular columns and coming to encased granular columns. Even encased of absence of the drainage, it can be seen the reduction in the settlement of granular column.

The vertical deformation of granular column is manifested here and similarly, the stiffer responses, in case of in case granular column as well.

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Response of granular column and geogrid to seismic loading

3D FD modeling of OGC and EGC

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Coming to the lateral displacement of these granular columns. So ordinary granular columns with no shear reinforcement and ordinary granular columns with shear reinforcement but no drainage and no additional densification. So, it reflects the trends that were seen in case of vertical displacement as well. So, this particular case experiences the most lateral deformation X direction.

And whereas the other cases performs in a stiffer manner and the reduction in even in this case, the respect to ordinary and in case granular columns given the same mechanisms, it is obvious. The difference is, it can be visually seen here.

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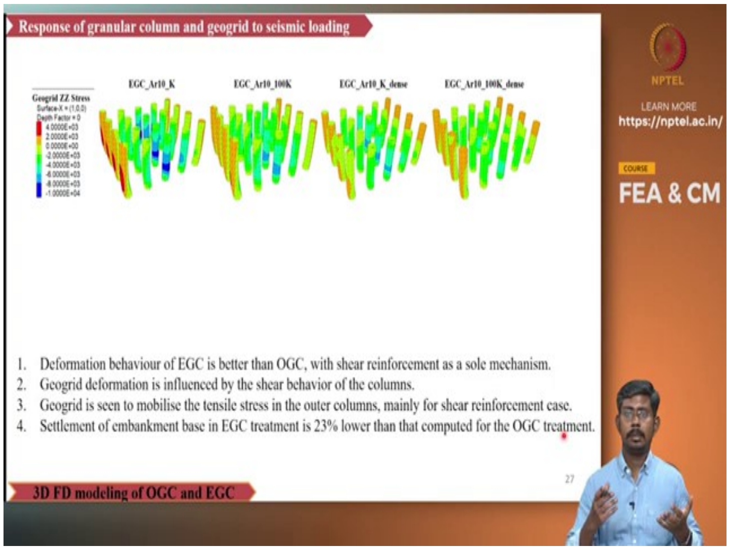

Response of granular column and geogrid to seismic loading

1. Deformation behaviour of EGC is better than OGC, with shear reinforcement as a sole mechanism.
2. Geogrid deformation is influenced by the shear behavior of the columns.
3. Geogrid is seen to mobilise the tensile stress in the outer columns, mainly for shear reinforcement case.
4. Settlement of embankment base in EGC treatment is 23% lower than that computed for the OGC treatment.

3D FD modeling of OGC and EGC

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And lastly, these stresses in the geogrid, so, it can be seen the tensile stresses are positive here. So, it is mobilized at the exterior columns that toward the lower half of the geogrid. So, this it is more pronounced in case of encased granular columns, where only the shear reinforcement is present. The additional drainage and the densification is not existing in this first case.

So, here it can be seen a greater mobilization of tens resources but this decreases as the columns become stiffer which means the mitigation mechanisms then drainage and densification which is which comes from the granular column. So that makes the geogrid not necessarily to mobilize the shear stresses not necessary to mobilize the tensile stresses. So, deformation behaviour of OGC is better than it was evident that the deformation behaviour of EGC is better than OGC.

Even when only the shear reinforcement is considered neglecting the drainage and the densification geography deformation is influenced by the shear behaviour of the columns. So, when the columns are stiffer so, the geogrid need not to mobilize the stresses which means it there is like the stresses are not transferred to it. So, the columns themselves behaves in a better manner and the geogrid is seen to mobilize the tenses in the outer columns predominantly further shear reinforcement case that is the first case.

And the settlement of embankment base in EGC treated ground is 23 percent lower than that of OGC treated ground. So, this the relative performance of ordinary granular columns and in case granular columns is demonstrated through 1G shaking table test, as well as a 3D numerical model.

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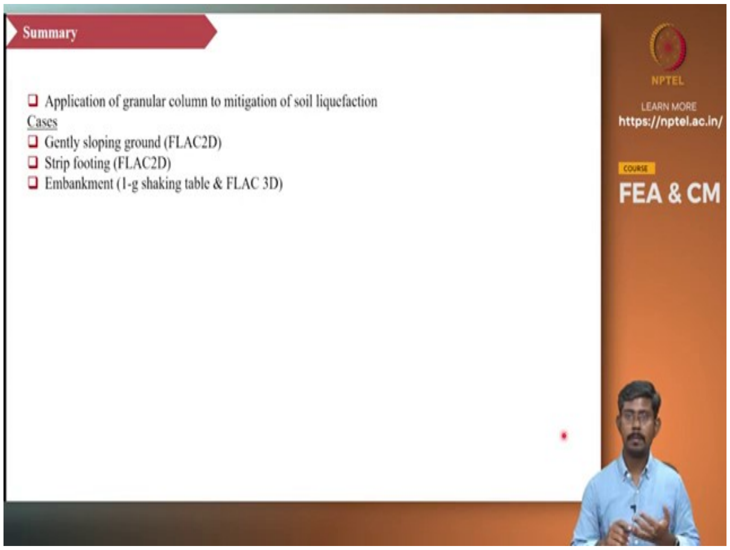

Summary

- ☐ Application of granular column to mitigation of soil liquefaction

Cases

- ☐ Gently sloping ground (FLAC2D)
- ☐ Strip footing (FLAC2D)
- ☐ Embankment (1-g shaking table & FLAC 3D)

So, coming to the summary, the application of granular columns to mitigate soil liquefaction was discussed. It was, firstly, the equivalent plane strain wall, consideration that is model in 2D that is, the structure is the level ground. The sloping ground case was considered and followed by the strip footing that was also modelled in 2D. And the embankment case was considered in both the experimental setup, as well as the 3D numerical model.