GEOTECHNICAL WEBINAR: GROUND IMPROVEMENT WORKS

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Ground Improvement Design Using MIDAS GTS NX

Two anonymised RI/CMC case studies

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Outline

- Brief RI/CMC introduction
- MIDAS GTS NX modelling strategy
- Case Studies Using Midas GTS NX
  Project A: Raised road embankment
  Project B: embankments behind bridge abutments
- Lessons learned
- Conclusions and discussion

RI/CMC and LTP with a layer of Geogrid

1. What are rigid inclusions?

Slender, high-stiffness columns installed through soft ground into a competent bearing layer, formed by displacement/ replacement augering with grout injection.

2. What problems do they solve?

They control total and differential settlement and improve bearing capacity wherever soft, compressible ground would govern the design.

3. How are they most commonly built?

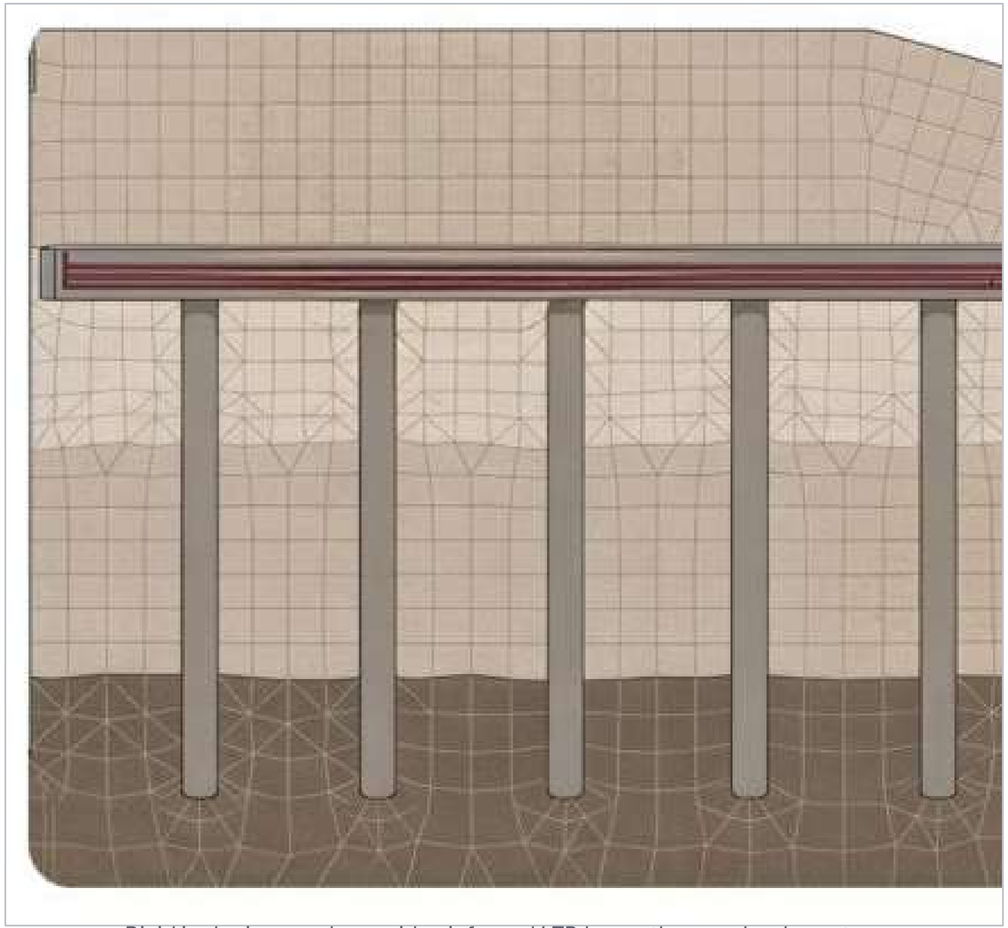
Installed on a square or triangular grid, typically 300-600 mm diameter, sized to the applied loading and ground conditions.

4. How does the system work?

The RI, surrounding soil and LTP act as a composite system, sharing loads through arching and stiffness contrast.

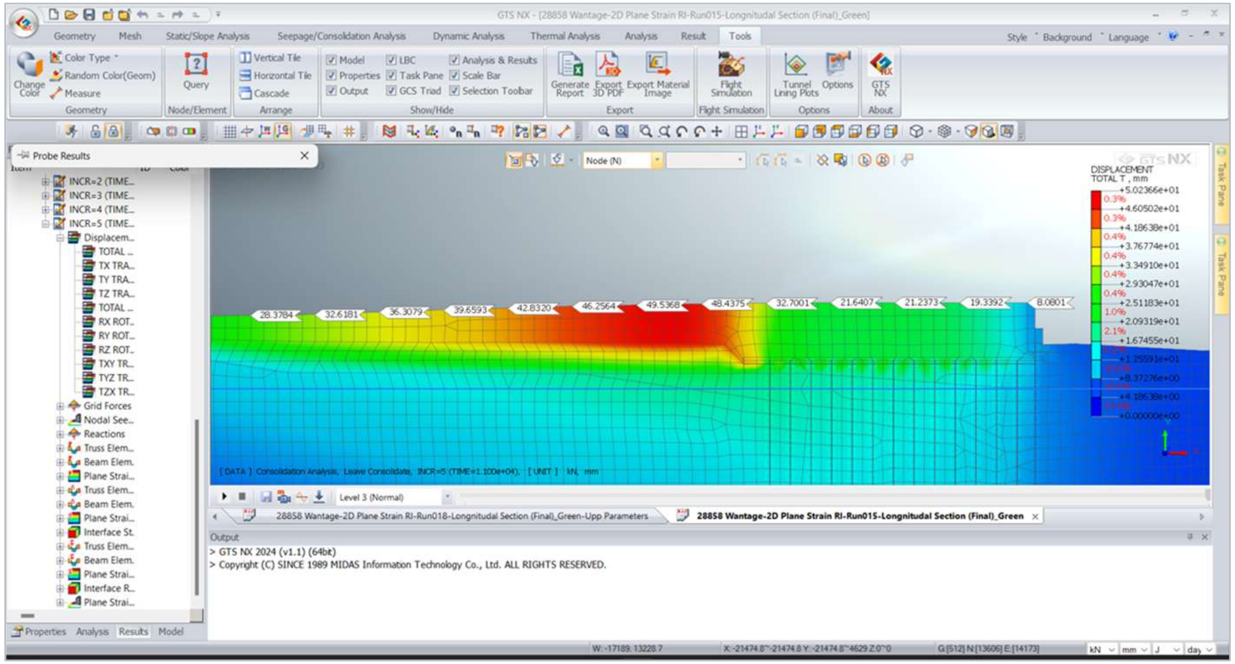
5. What is the desired outcome?

To reduce stress in compressible soils strata and control deformation by sharing loads with the surrounding ground.



Rigid inclusions and geogrid-reinforced LTP beneath an embankment.

MIDAS GTS NX connects the ground model to performance checks to evaluate settlements before and after ground improvement, stress redistribution and axial forces within the inclusions.



MIDAS GTS NX Workflow

BUILDING THE MODEL

Geometry

Soil constitutive models

Generate mesh

(CALIBRATION)

SETTING UP CONSTRUCTION STAGES

PERFORM CASE ANALYSIS

RESULTS

Note:
2D analysis in geotechnical projects is popular for its speed, simplicity and competitive costs compared to 3D analysis. To ensure accuracy and reliability all model's parameters should be verified and validated to better represent reality and the reliability at which the results from computational models can be used in the design process.

Modelling Strategy

Geometry?

A good finite-element model should use the simplest geometry that still captures the important features influencing the key outputs. Unnecessary detail should be avoided to achieve a practical balance between accuracy, computational efficiency and modelling time.

Soil constitutive model?

The constitutive model should reproduce the material behaviour that most strongly influences the required outputs over the anticipated stress paths and strain ranges. The simplest suitable model should be selected, considering the analysis objectives, structure type, construction sequence, ground conditions and availability of reliable input parameters; no single model is appropriate for every application or stress path.

Generate mesh?

A good finite-element mesh is graded, using smaller, well-shaped elements near stress concentrations, stiffness changes, discontinuities, foundation corners and pile bases, with larger elements in areas of relatively uniform behaviour. Mesh convergence should be checked by progressive refinement until key outputs remain essentially unchanged, while avoiding excessively distorted elements.

Setting up construction stages?

A geotechnical finite-element analysis should represent the essential construction sequence and timing because loading, pore-pressure dissipation and creep influence the stress path and final behaviour. Construction stages should use appropriate activation and deactivation of elements, while unnecessary details may be omitted only when sensitivity analyses confirm that key outputs are not significantly affected. Ground improvement processes, such as compaction or treatment, are generally represented by changing the soil strength, stiffness and density parameters at the relevant construction stage, using values derived from site trials or experience on comparable projects.

Consolidation Analysis Drained or Undrained?

The choice between drained, undrained and consolidation analysis depends on the relationship between the loading rate and the rate of pore-pressure dissipation. Drained analysis is appropriate when drainage occurs faster than loading, whereas undrained analysis represents short-term conditions with negligible dissipation; consolidation analysis is required for partially drained construction or for predicting the time-dependent dissipation of excess pore pressures, deformation and changes in structural forces. Because consolidation rates depend strongly on uncertain soil permeability and drainage-path conditions, sensitivity analyses should be undertaken when consolidation time is important.

Ground improvement system: a composite solution comprising the RIs , surrounding soil and LTP

The primary challenge for both projects was to reduce/mitigate settlements

PROJECT A

- Residential development
- 2.4 m high embankment
- Very soft Marine Clay deposit up to 13.65 mBGL
- 350 mm RI/CMC at 2.2 m c/c on a square grid
- Settlement criterion: ~50 mm

PROJECT B

- Bridge approaches up to ≈4.30 m high
- Soft zone up to 7.70 mBGL
- 350 mm RI/CMC at 1.60 m c/c on a square grid
- 20 mm over 5 m near abutments
- Longitudinal gradient ≤ 1:250

Interaction between components satisfy ULS and SLS requirements.

Design assessed load-transfer mechanisms, bearing resistance, total and differential settlement, and overall stability.

RIs redistribute load through the composite ground mass and limit the excessive settlement that would otherwise occur beneath the road embankments and associated drainage infrastructure.

Project A

Raised road embankment adjoining residential plots over deep Marine Clay

Project A: required a practical treatment across the full embankment footprint. Treatment supports roads and drainage infrastructure, while adjacent houses are founded on piled ground beams.

2.4 m

maximum embankment height to raise finished levels above a flood-prone area

~50 mm

Limit of differential settlement in the embankment which supports roads and drainage infrastructure

485 mm

predicted untreated settlement

The ground improvement system includes:

- **Geosynthetic-reinforced LTP above RI/CMC system to distribute applied loads.**
- **All RI/CMC elements were specified with a nominal diameter of 350 mm.**
- **RI/CMC elements of the embankment arranged in a square grid (2.2 m × 2.2 m).**

Project A: The ground model is governed by a deep, variable Marine Clay layer

MADE GROUND / FILL	Surface variability
MARINE CLAY	Very soft silty clay, locally sandy or gravelly: up to 13.65mBGL, with representative/average thickness roughly 7.2m
DRIFT DEPOSITS	Intermediate materials
WEATHERED CHALK → CHALK	Competent founding strata with local hard bands

Evidence base:
Soil description from CPTUs, BHs, trial pits
Ground water regime evaluated from dip meter and pore pressure dissipation tests | Groundwater: at 0.5 mBGL
Strength evaluated from CPTUs and strength laboratory testing
Consolidation and compressibility behaviour of soils evaluated from pore pressure dissipation tests and oedometer testing

Project A: Soil constitutive models

Soft Soil model

- Used to model the Marine Clay

- Logarithmic stress–strain relationship, with stiffness linearly dependent on p'.
- Plastic strains during primary compression (compaction hardening).
- Elastic behaviour during unloading and reloading.
- M is based on K_0^{nc} under one-dimensional compression rather than on f'.
- Failure behaviour is governed by the Mohr–Coulomb criterion.

Parameters:
normal consolidation line slope (λ) and over-consolidation line slope (κ),c', f', γ, K_0^{nc} Horizontal-to-vertical effective stress ratio under normally consolidated one-dimensional compression; used to determine M.

Mohr-Coulomb model

- Used to model the Made Ground, Drift, Chalk, LTP and embankment fill

- Elastic perfect plastic

- Failure criteria is Mohr Coulomb

- State of stress is isotropic

Parameters:
c', f', γ, E (considered as E_{50}), u

Note:
Soft Soil model no time-dependent behaviour.
Mohr-Coulomb provides a stable strength and stiffness idealisation for other materials.

Project A: FE adopted strength and stiffness parameters

Material	γ (kN/m³)	ϕ′ (°)	c′ (kN/m²)	C_u (kN/m²)	E_{oed} / E_{50} (MN/m²)
Made Ground	18.0	28	1	n/a	12 / 12
Marine Deposits	15.0	20	2	10	0.77 / 1.5
Drift Deposits	18.0	25	1	n/a	28 / 28
Weathered Chalk	18.0	25	1	n/a	28 / 28
Chalk to depth	18.0	33	1	n/a	50 / 50
Embankment	20	36	1	n/a	50 / 50
LTP	20	45	1	n/a	45 / 45

Note:
Sensitivity analyses were undertaken to assess how parameter variability (in particular permeability) affects rate and magnitude of settlement.
The analysis is performed using the drained parameters in short and long term. In short term the settlement prediction is relatively higher than the analysis under undrained conditions.

Project A: FE adopted state and consolidation parameters

Material	OCR	e_0	λ	κ	k (m/day)
Made Ground	1	0.5	n/a	n/a	1×10^{-2}
Marine Deposits	1	1.1	0.17	0.035	1×10^{-6}
Drift Deposits	1	0.5	n/a	n/a	1×10^{-3}
Weathered Chalk	1	0.5	n/a	n/a	1×10^{-3}
Chalk to depth	10	0.5	n/a	n/a	1
Embankment	n/a	0.5	n/a	n/a	1
LTP	n/a	0.5	n/a	n/a	1

Note:
λ and κ are used in the very soft Marine Clay deposit; permeability, k controls the consolidation rate.

Project A: using 2.2 m square grid and reinforced LTP reduced stress in the very soft Marine Clay deposit

Component	Adopted design
RI/CMC diameter	350 mm
Grid spacing	2.2 m × 2.2 m
Inclusion length	To refusal depth (approximately 12–18 m, which varied with ground profile)
Load Transfer Platform	500 mm minimum
Reinforcement	Biaxial geogrid

Note:
A calibrated 2D plane-strain approach was adopted because the soil profile varies substantially along the embankment and is difficult to represent efficiently in a full 3D model. The embedded-beam parameters were calibrated in a 2D plane-strain unit-cell model against a reference axisymmetric model, in which the RI was represented by solid elements. The calibrated parameters were then applied in the full 2D embankment analysis.

Project A: Model Calibration

Why 2D plane strain calibration is important?

It is difficult for a 3D model to represent efficiently soil variability along the embankment

What is the 2D cross section?

2.4 m high embankment stabilised by 350 mm diameter rigid inclusions installed in a 2.2 m square grid. Inclusion termination was governed by project-specific refusal criteria to account for variability and hard bands within Chalk.

What is the calibration target?

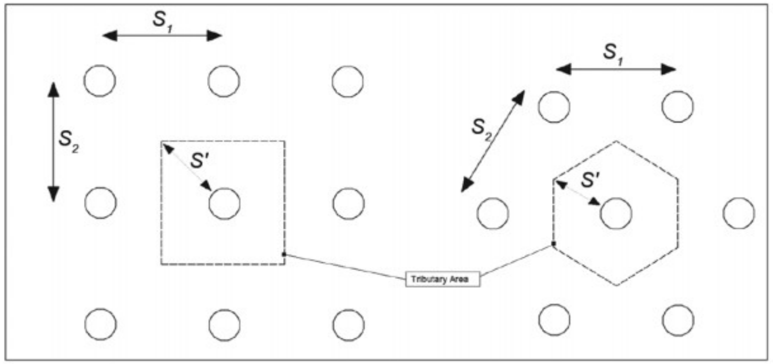
Match the inclusion-head load, axial-force distribution with depth and toe force from a reference axisymmetric solid-element model.

Where are the calibration factors applied?

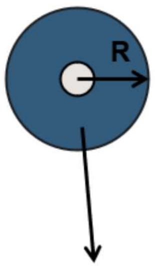
Selected calibrated factors are applied in the final 2D plane-strain model to assess settlement and RI/CMC axial forces.

Project A: Model Calibration

The reference axial-load response was first established using an equivalent axisymmetric unit-cell model for a square inclusion pattern



Influence zone for a square grid: $A = s^2$



Equivalent axisymmetric cell: $s^2 = \pi R^2$ For s = 2.2 m, R ≈ 1.24 m

Calibration steps:

- Embedded beam elements with $E=5\times10^6$kPa and a reference axisymmetric model represent RIs.
- Drained loading during embankment construction and consolidation simulate excess pore-pressure dissipation stress redistribution.
- Equivalent 2D plane-strain unit cell model reproduces the reference model's response.
- Calibration begins by matching the force transferred at the RI head.
- Axial stiffness factor is adjusted to reproduce the axial force distribution with depth.
- Base stiffness factor is adjusted to match the force at the inclusion toe.
- Sensitivity checks using different interface factors produce similar axial force results.

Project A: Staged construction captured short- and long-term consolidation

01

Initial state

Establishment of the in-situ stress regime and groundwater conditions

02

Construction of RI/CMC + LTP

10-day consolidation period following installation to represent the short-term response prior to embankment construction

03

Embankment

Placement of the embankment fill to the proposed formation level; 40-day construction period

04

Long term

Assessment extended to 20 years

Note:
The staged construction sequence enables assessment of both short-term and long-term settlement performance, including the effects of stress redistribution, excess pore pressure dissipation and consolidation within the soft Marine Clay deposits underlying the proposed embankments.

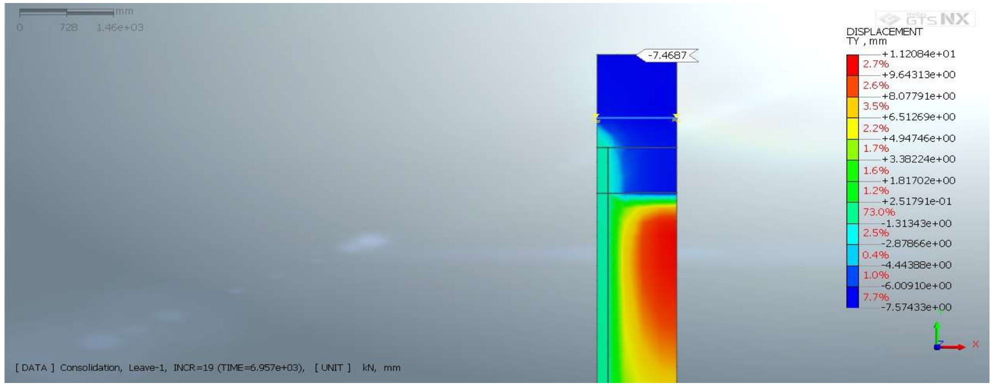
Project A: Results

The main output:

- **Settlement contours**
- **Vertical displacement**
- **Stress concentration**
- **Inclusion axial-force distribution**
- **Pore-pressure dissipation**
- **Comparison between untreated and treated ground**

Axisymmetric model with interface 0.4

20-year displacement response from the axisymmetric solid-inclusion model.

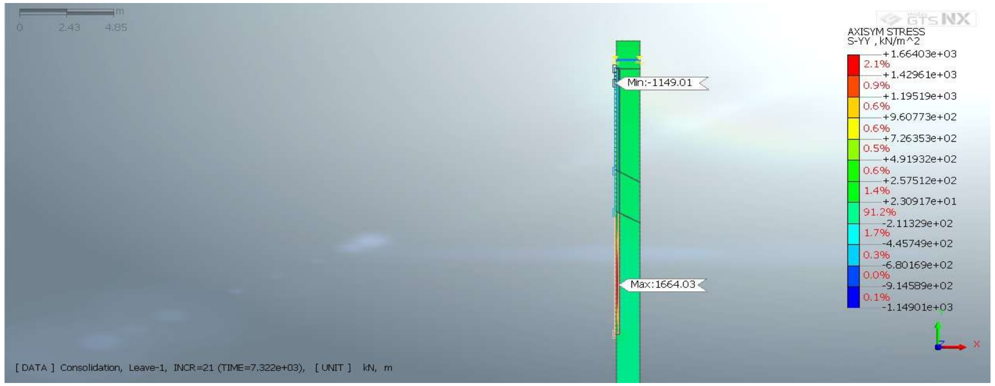


Axisymmetric model without interface

Removing the interface changes both deformation and stress-transfer behaviour.

Note:
The axisymmetric model was used as the higher confidence reference before simplifying the RI/CMC representation for plane strain.
Various values for interface factor are used in the calibration model to assess the ranges of settlements and forces. For the very soft Marine Clay deposit the interface factor used is unusually low to account for the higher possible settlement as the most unfavorable soil behaviour.

The vertical stress comparison complements the displacement calibration: both deformation and load transfer were checked before adopting the simplified 2D representation.



Vertical stress — with interface

Axisymmetric vertical stress distribution with the RI/soil interface active.

Vertical stress — without interface

Without the interface, the axial stress distribution and shaft load-transfer mechanism change.

Axisymmetric model with interface 0.8

20-year displacement response from the axisymmetric solid-inclusion model.

Vertical stress — with interface 0.8

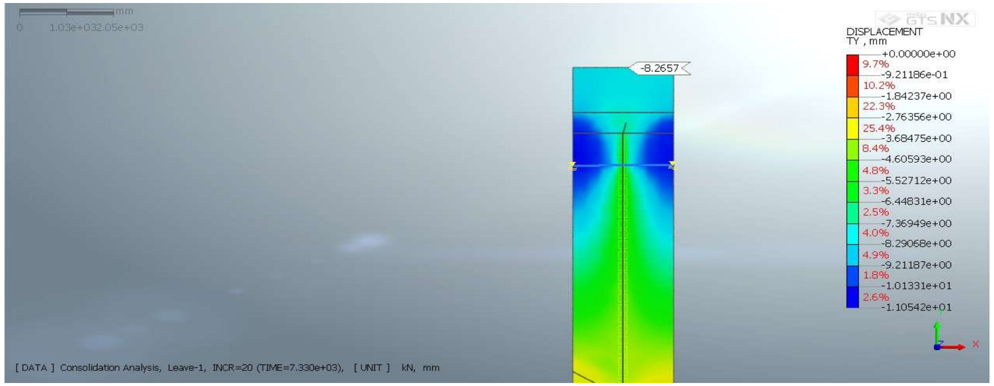
The 2D unit cell was calibrated against the axisymmetric reference

Displacement — interface factor 0.4

The reduced interface factor reproduced the reference deformation response in the unit-cell calibration.

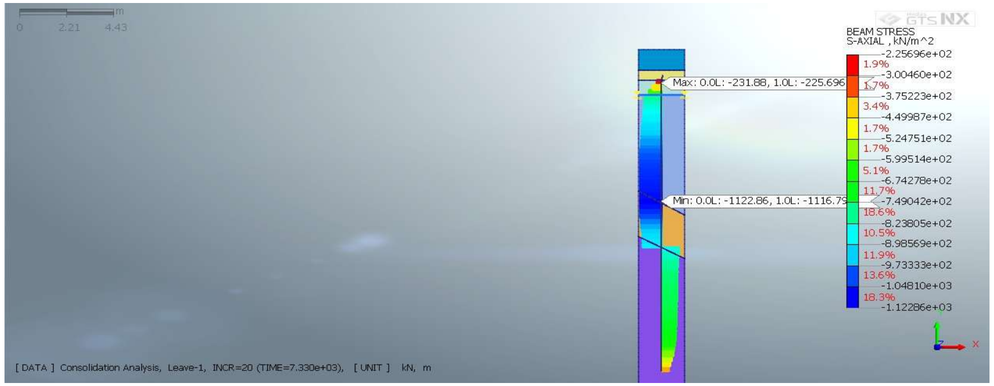
Vertical stress / RI response

Stress transfer along the embedded RI was checked at the same calibration stage.



Unit cell — interface factor 1.0

A higher interface factor was also assessed as part of the calibration sensitivity study.



RI stress response — interface factor 1.0

The stress-transfer response remained part of the acceptance check.

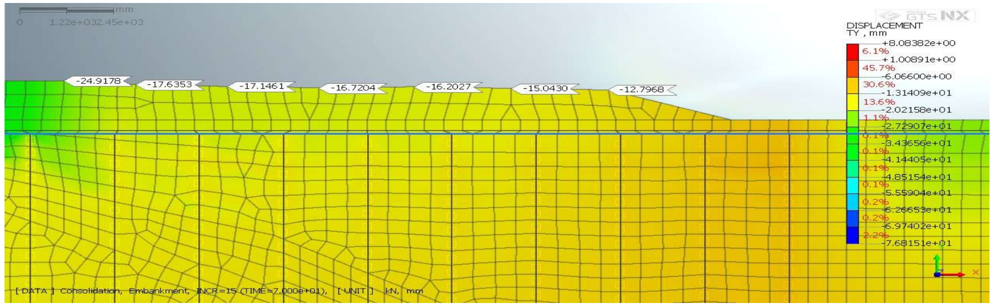
Sensitivity checks supported the interface adopted for the embankment model

Unit cell — interface factor 0.8

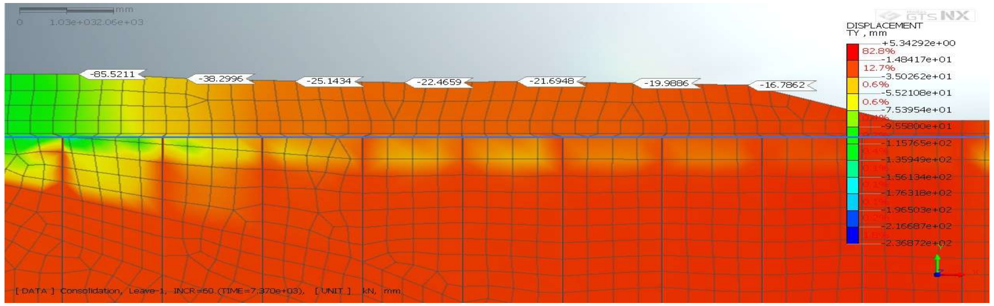
RI stress response — interface factor 0.8

An interface factor of 0.8 was adopted following the calibration and sensitivity checks.

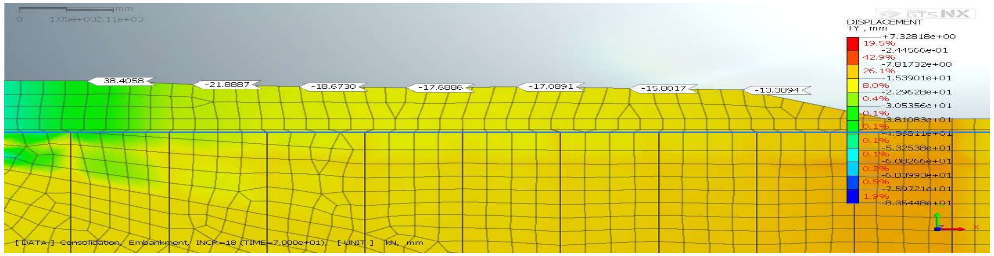
Time depended settlement results



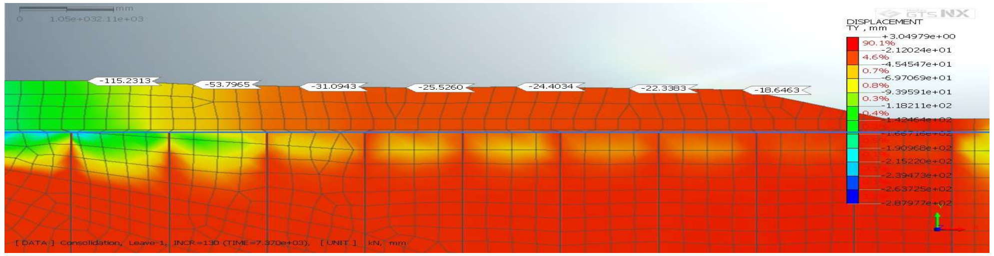
k = 1 × 10^{-6} m/day — after construction



k = 1 × 10^{-6} m/day — 20 years



k = 1 × 10^{-5} m/day — after construction



k = 1 × 10^{-5} m/day — 20 years

The contours show the same governing section at construction completion and after 20 years, explicitly demonstrating the sensitivity of consolidation behaviour to the assumed soil permeability.

Project B

Embankments behind bridge abutments

Project B combines a 4.3 m embankment with strict transition criteria

4.3 m

maximum embankment height

20 mm over 5m

Maximum differential settlement from the rear face of each abutment

1:250

Maximum longitudinal differential-settlement gradient

The ground improvement system includes:

- **Geosynthetic-reinforced LTP above RI/CMC system to distribute applied loads and manage the stiffness transition between the piled abutment and improved approach embankment.**
- **All RI/CMC elements were specified with a nominal diameter of 350 mm.**
- **RI/CMC elements on both sides of the abutment arranged in a square grid (1.6 m × 1.6 m).**

Project B: Soil constitutive models

Soft Soil model

- Cohesive Alluvium and Soft Gault Clay

- Logarithmic stress–strain relationship, with stiffness linearly dependent on p'.
- Plastic strains during primary compression (compaction hardening).
- Elastic behaviour during unloading and reloading.
- M is based on K_0^{nc} under one-dimensional compression rather than on f'.
- Failure behaviour is governed by the Mohr–Coulomb criterion.

Parameters:
normal consolidation line slope (λ) and over-consolidation line slope (κ),c', f', y, K_0^{nc} Horizontal-to-vertical effective stress ratio under normally consolidated one-dimensional compression; used to determine M.

Hardening Soil model

- Competent Gault Clay, Lower Greensand and Kimmeridge Clay

- Stress-dependent stiffness behaviour governed by a power law.
- Hyperbolic stress–strain relationship during primary axial loading.
- Plastic strains caused by mobilised friction (shear hardening).
- Plastic strains during primary compression (compaction hardening).
- Elastic behaviour during unloading and reloading.
- Failure behaviour governed by the Mohr–Coulomb criterion.

Parameters:
$E_{50,}{}^{ref}$, $E_{oed,}{}^{ref}$, $E_{ur,}{}^{ref}$, m, p^{ref}, c', f', y,u_{ur} K_0^{nc}

Note:
Soft Soil model no time-dependent behaviour.
Hardening Soil captures the stress-path-dependent stiffness of the competent strata.

Project B: FE strength and stiffness inputs

Material	γ (kN/m³)	ϕ′ (°)	$E_{oed,}^{ref}$ (MN/m²)	$E_{50,}^{ref}$ (MN/m²)	$E_{ur,}^{ref}$ (MN/m²)
Alluvium Granular	19.0	32	10	10	30
Alluvium Cohesive	19.0	22	3.5	7	n/a
Gault Clay Soft	19.0	22	4.5	9	n/a
Gault Clay	19.0	22	10.255	20.5	61.5
Upper Greensand	22.0	24	39.25	78.5	235.5
Kimmeridge Clay	21.0	23	12.745	25.5	76.5
Embankment / LTP	20	36 / 40	n/a	50	n/a

Project B: FE adopted state and consolidation parameters

Material	OCR	POP (kN/m²)	e_0	λ	κ	k (m/day)
Alluvium Granular	1	—	0.5	—	—	1
Alluvium Cohesive	2.1	—	0.53	0.0586	0.0117	8.64×10^{-4}
Gault Clay Soft	—	98	0.68	0.303	0.0061	3.54×10^{-4}
Gault Clay	3.8	—	0.5	n/a	n/a	3.54×10^{-4}
Upper Greensand	9.3	—	0.5	n/a	n/a	1
Kimmeridge Clay	3.3	—	0.5	n/a	n/a	8.64×10^{-5}
Embankment / LTP	n/a	—	0.5	n/a	n/a	1

Project B: The proposed RI/CMC arrangement was assessed by 2D and 3D FE analyses

2D plane strain

- Represents the longitudinal road alignment
- Developed to evaluate the overall settlement response of the embankment and to undertake sensitivity analyses
- RIs were modelled as embedded beam elements with an equivalent E=5 × 10^6 kPa
- Model includes bridge abutments and piles for realistic transition of stiffness
- Differential settlement assessment and sensitivity analysis

3D group model

- Developed to investigate the local behaviour of the composite ground system
- Developed to assess the interaction between the RIs, LTP and surrounding soils.
- Model comprising 350 mm diameter inclusions installed at 1.6 m centres in a square grid configuration, with 4 × 4 inclusion group
- RIs represented by volumetric concrete elements capturing 3D stress transfer mechanisms and system interaction

Note:
2D and 3D analyses are used to verify the adequacy of the proposed RI/CMC arrangement and to demonstrate compliance with the project settlement criteria for total and differential settlement.
(2D and 3D FEM use coupled consolidation analyses to assess the time-dependent response of the soft compressible strata under the proposed embankment loading.
The consolidation analyses account for the generation and dissipation of excess pore water pressures, enabling prediction of both the magnitude and rate of settlement development within the underlying cohesive soils.

Project B: Staged construction sequence extended from installation to 20-year operation

01

Initial state

Establishment of the in-situ stress regime and groundwater conditions

02

Installation

A consolidation period of 10 days was allowed after RI/CMC and LTP installation

03

Construction

Embankment was simulated over a period of 30 days

04

Initial Settlements

A period of 10-day was allowed post completion for pore water pressure dissipation and initial settlements development

05

Operational Surcharge Loading

A uniform10 kN/m^2 surcharge was applied at road level allowing 10 years consolidation period.

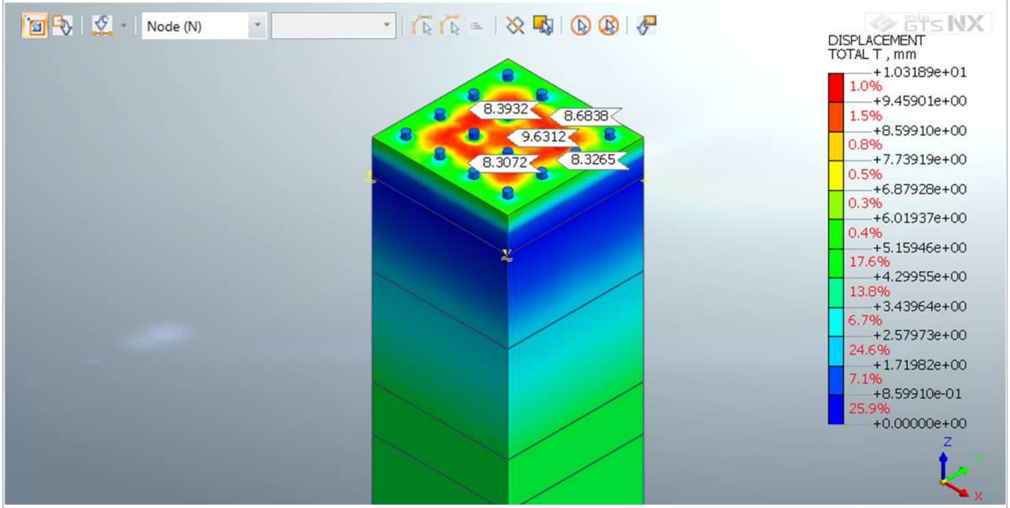
06

Long-Term Consolidation Assessment

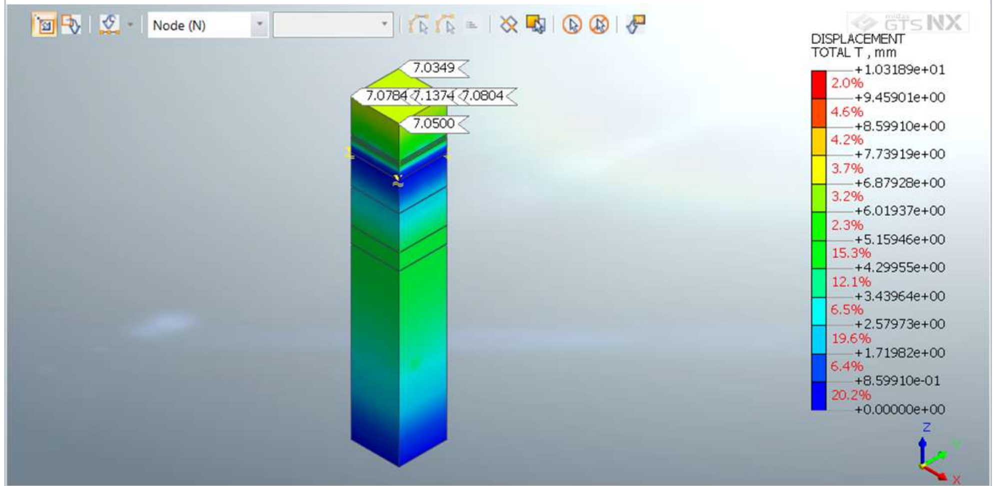
Extended to 20 years

Project B: Results

Validation check: The 3D group model revealed settlement and load sharing within the RI



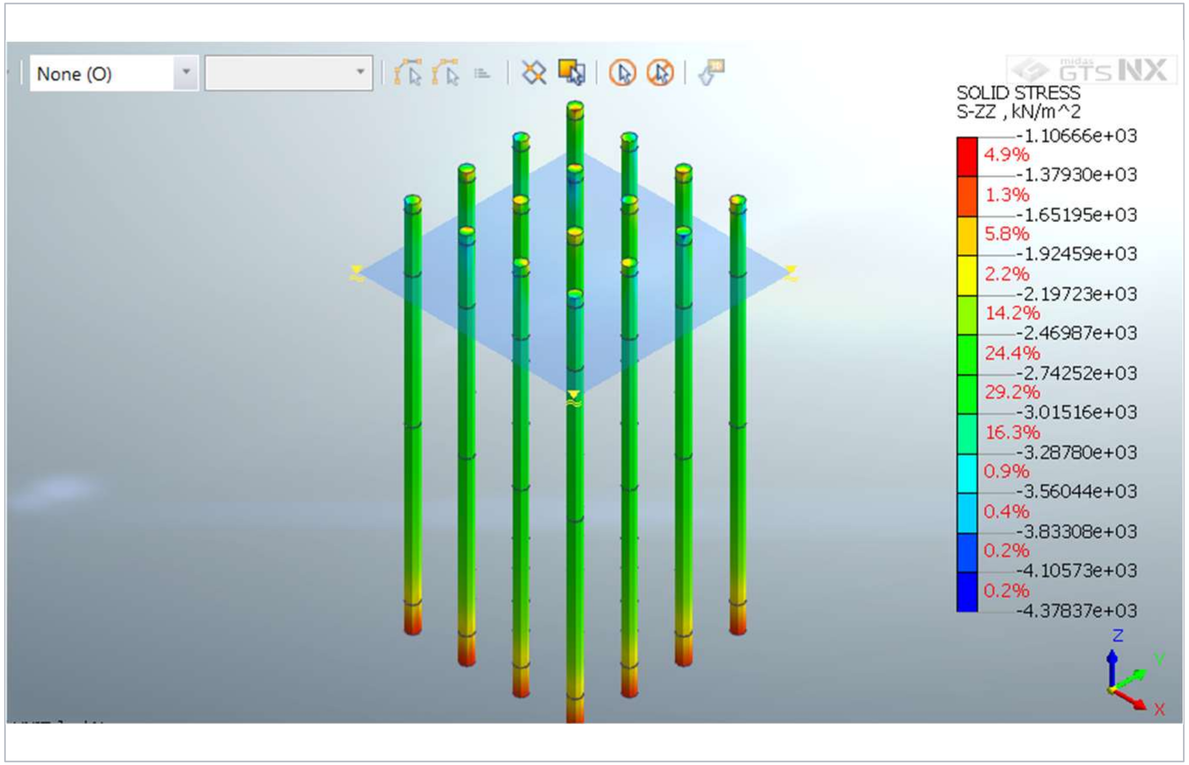
Group settlement response



Local inclusion response

Project B: Results

Stress integration independently confirmed the extracted axial loads



3,288 kPa

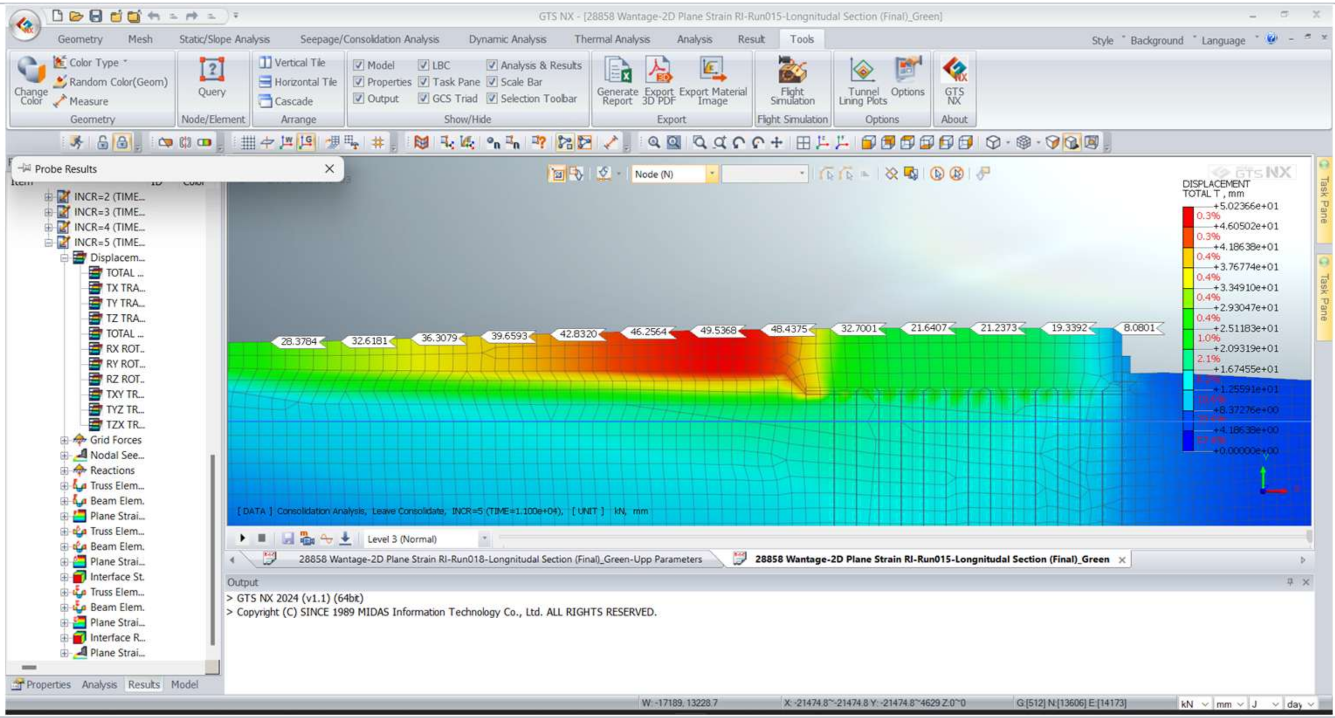
maximum vertical stress

≈316 kN

equivalent axial load

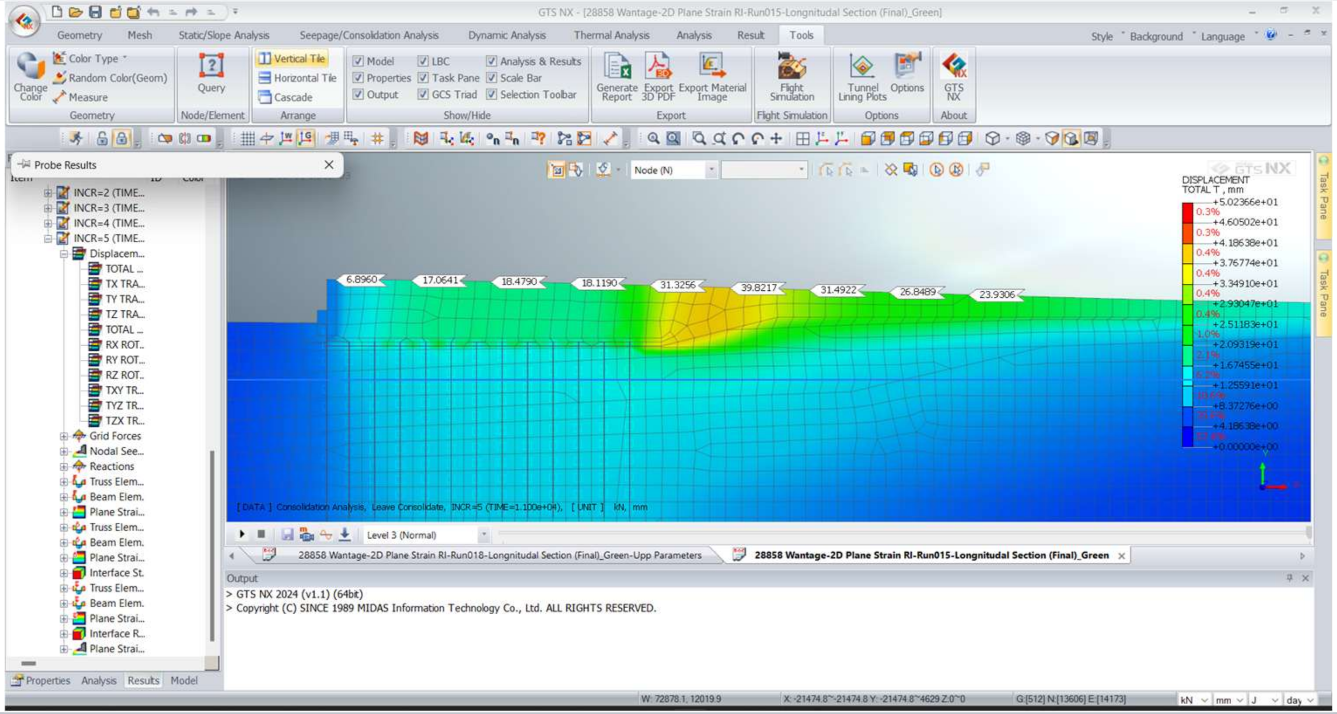
Project B: Results

Settlement contours for the north abutment



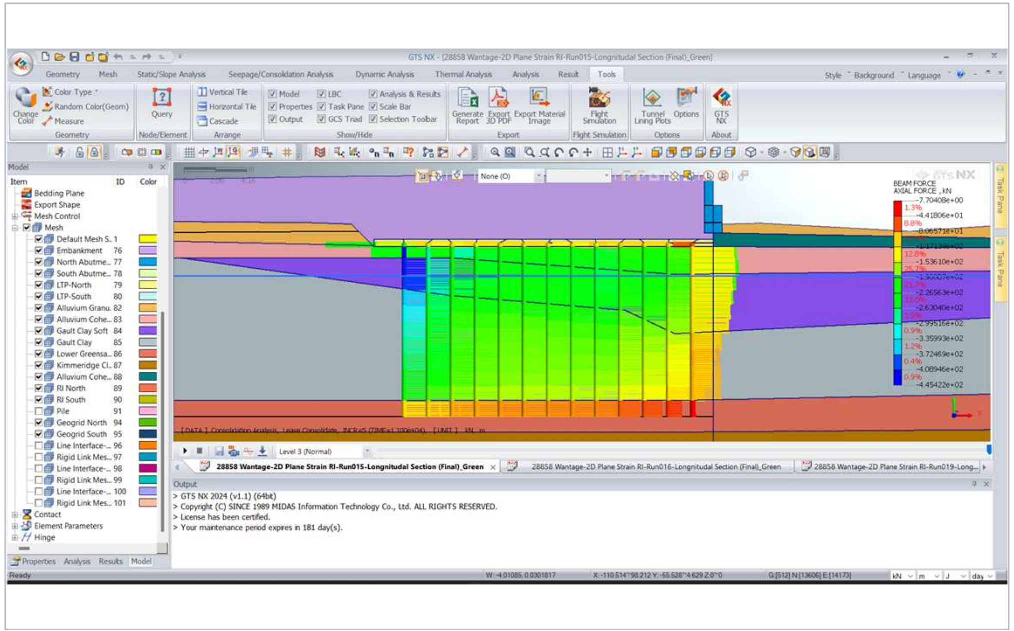
Project B: Results

Settlement contours for the south abutment

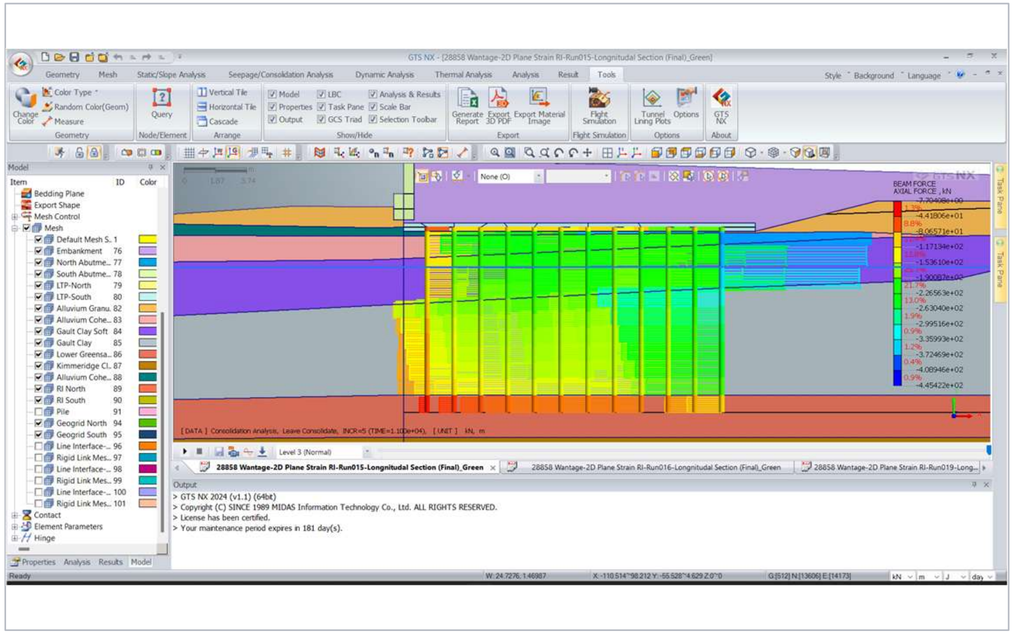


Project B: Results

2D model axial forces for both bridge abutments



North Abutment



South Abutment

Edge inclusions carried the highest axial forces

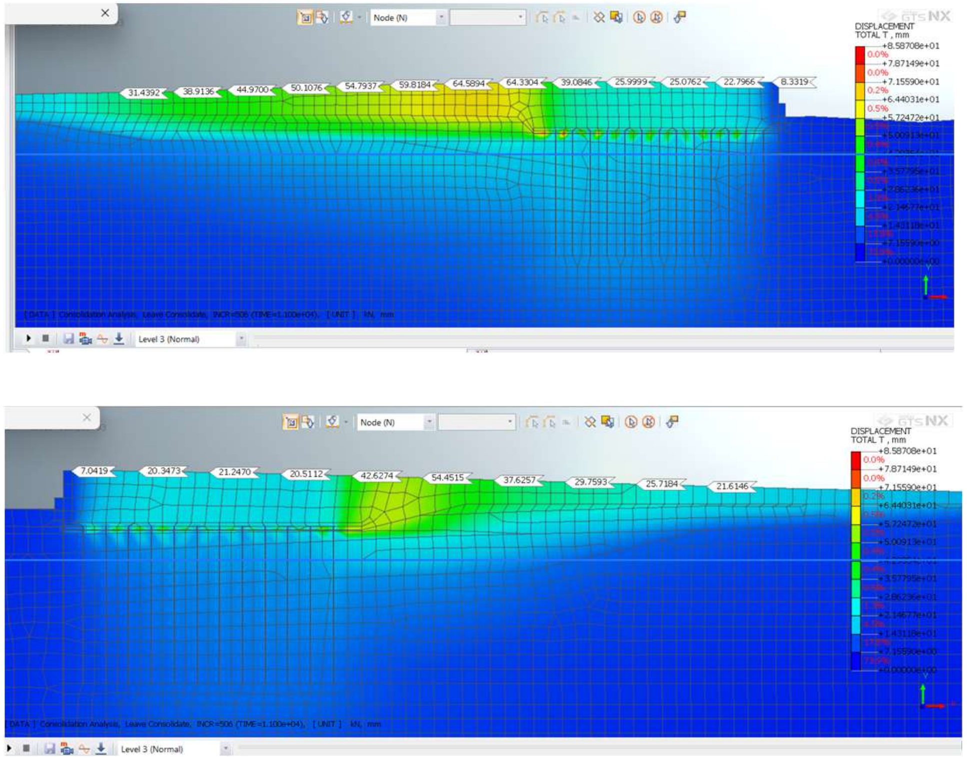
≈300 kN Typical inclusion axial force

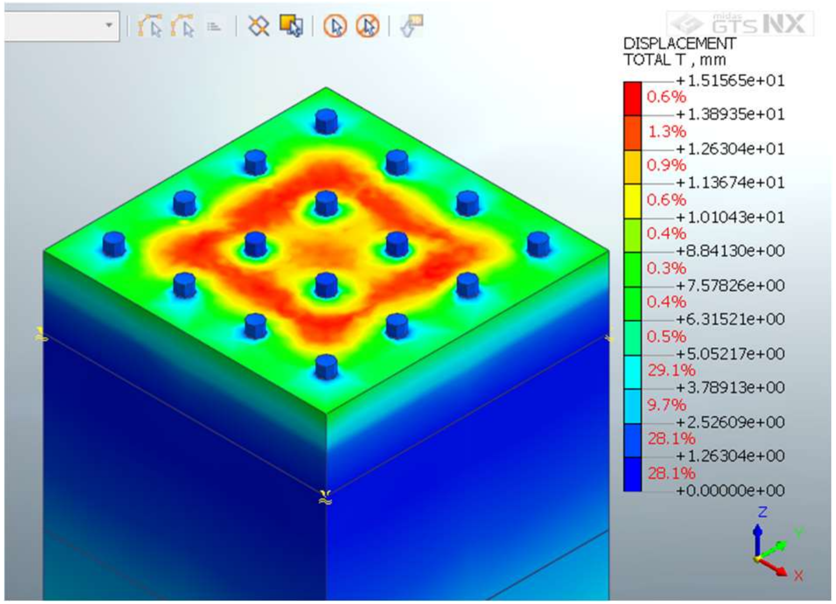
≈445 kN Outermost-row edge RI

≈316 kN Stress-derived verification

Project B: Results

The sensitivity analysis was undertaken using a range of l and k outliers values adopted for design.





Aspect	Project A	Project B
Primary risk	Deep consolidation settlement	Abutment transition movement
Soft ground	Marine Clay to ≈13.65 mBGL	Alluvium + Soft Gault Clay to ≈7.7 mBGL
Grid	2.2 m × 2.2 m	1.6 m × 1.6 m
Numerical focus	Calibrated 2D plane strain	Combined 2D alignment + 3D group
Key verification	≈50 mm long-term settlement	Differential criteria and inclusion forces

- **Build the ground model from multiple investigation sources**
- **Match constitutive models to the expected soil response**
- **Calibrate simplified structural elements against a higher confidence reference**
- **Model the real construction sequence and consolidation time**
- **Cross-check settlement and inclusion forces using independent methods**

- **Both projects demonstrate the successful use of RIs to control settlement on soft ground.**
- **The MIDAS GTS NX analyses confirmed that the proposed ground improvement systems satisfy the project performance criteria while enabling detailed assessment of settlement, consolidation and load transfer.**
- **An interface reduction factor (<1) should be adopted to represent the reduced shear strength mobilized at the soft soil – RI interface. Sensitivity analyses are recommended, as lower values reduced shaft resistance and modify the load transfer mechanism.**
- **A higher interface factor is recommended at the RI head with the RI-LTP interaction zone to provide a more realistic representation of load transfer. This promotes greater load attraction to the RI and reduce stresses transferred to the surrounding soft soil, better representing the expected arching mechanism within the LTP.**

Thank you for your attention

Questions & Discussion