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Increasing Amsterdam quay wall stability through Bio-Inspired Soil Improvement

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ABSTRACT

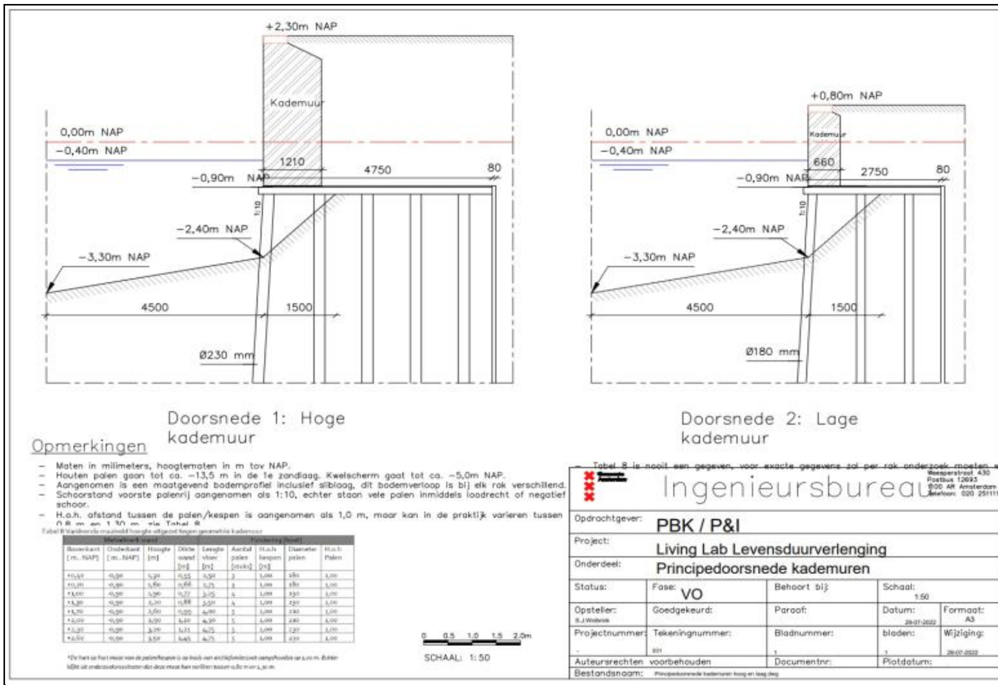
Bio-inspired soil improvement is being considered as a cost-effective method to improve longevity of the heritage Amsterdam quay walls. Bio Inspired Soil Improvement (BISI) employs processes that are based on natural soil biology or implement similar processes with the aim of changing the geotechnical (physical) properties of soils. Microbially Induced Carbonate Precipitation (MICP) causes precipitation of calcium carbonates (mostly as calcite) by in-situ biogeochemical processes. These precipitates have potential to improve sediment stiffness, strength, and dilatant behaviour through inter-particle bonding and sediment particle surface roughening, commonly referred to as bio-cementation. As it can be applied in a minimally invasive manner, bio-cementation offers the potential for cost-effective cementation of the granular fill behind the Amsterdam quay walls, diverting stresses from the quay wall to the foundations. Achieving acceptance of BISI to stabilize historic quay walls is a complicated process, starting with introducing the concept to the City staff, who defined 10 different failure modes. Geotechnical modelling of the quays and modifying relevant parameters based on published effects of BISI gives insight on the required level of cementation and dimensions of the cemented soil mass to sufficiently improve stability. We tested various recipes, formulations, and modes of treatment in laboratory experiments on material from Amsterdam quays. The fill behind the quay walls is 'made ground' of vastly varying composition (sand, silt, clay, peat, demolition and other wastes), which are not all amenable to the MICP process. We assessed the composition of the fill material statistically, to conclude that BISI could be a viable option for improving the stability of 70 – 80% of the quays.

INTRODUCTION

The historic Amsterdam city-centre quays were constructed between 1700 and 1850, using then state-of-the-art engineering. Figure 1 shows a typical cross section. The construction comprises of wooden piles, driven to a sand layer at approximately 12 m below NAP (Dutch Ordnance Datum). Inward of the inner-most piles, a vertical (wooden) barrier was placed to (later) prevent outwash of soil from behind the quay. A set of wooden beams and planks on top of the piles creates a platform. On that platform, a masonry quay wall is built, with a slightly tapered inner face. At the top of the wall, stone slabs are placed. The masonry wall derives its stability against tipping forward solely from its mass; it is not anchored to the construction underneath. A slightly elevated ridge at the outer side of the platform prevents the quay wall from sliding into the canal. The space behind the quay is filled with available materials; often sand (but other local soils and demolition waste may also have been used). Finally, the canal is dug to its designed profile.

The quays have historically stood well up against increasingly dense and heavy traffic but are now at risk of failure. Replacing all 205 km of quay walls at risk with modern concrete and steel constructions is prohibitively expensive (estimated at €40K per metre) and would cause unacceptable disruption to city life. Therefore, Amsterdam is searching for alternative solutions that would stabilize quays for 30 – 50 years.

Amsterdam identified 10 modes of failure for its quays. The failure mode of quay wall failure trough rotation was selected to be reviewed for potential mitigation using Bio Inspired Soil Improvement. This failure mode is caused by increasing outward horizontal pressure onto the quay wall by the soils behind the quay walls. The cause of this increasing pressure is predominantly the increase in stress caused by modern traffic (in terms of weight and vibration). Initially, two BISI approaches were considered for mitigation: cementation through microbially or enzymatically induced precipitation of calcium carbonates (MICP or EICP) and desaturation trough formation of



All dimensions are in mm (unless otherwise indicated)
NAP is Dutch Ordinance Datum (equivalent to average sea level); water level in the canals is strictly regulated at 0.40m – NAP
The quay wall ('Kademuur') is built using brick and mortar; all other parts of the construction are wooden.
Wooden pilings were driven to approximately 13.5 m-NAP, into a sand layer; outer piling was installed askew (1:10 slope)
Drawing courtesy Ingenieursbureau Amsterdam

Figure 1. Typical cross section through Amsterdam quays

N_2 gas by reduction of nitrates combined with some calcium carbonate formation (MIDP, or microbially induced desaturation and precipitation).
BISI can reduce the pressure on the quay walls by diverting the pressure inside the soil behind the quay walls or by reducing the mass of material (through desaturation). As the groundwater level behind the quays is close to the canal level, which is a few decimetres above the wooden platform, most of the soils behind the quay walls are in the unsaturated zone, which contains oxygen. MIDP can only work in reductive/anoxic conditions, which would be difficult to establish in this case. The effect of mass reduction by partially desaturating the 0,5 m saturated zone behind the quay walls would be minimal. Therefore, calcium carbonate formation via MICP or EICP was selected as the preferred BISI alternative. MICP was selected over EICP as it was anticipated that the slower MICP process would be better amenable to the required distribution processes of amendments in the soils behind the quay walls. While MICP is well proven in laboratory conditions, only a few cases of full-scale application are documented (e.g. Zeng et al, 2021). The process of developing MICP from the current level of this technology to ‘ready for full scale’ for stabilization of the Amsterdam quay walls is expensive and requires proper management.

PROJECT IMPLEMENTATION

The development stage of MICP technology may be defined using the Technology Readiness Level (TRL) (NASA 1988, EARTO 2014), a system adapted by many including Rijkswaterstaat (https://rwsinnoveert.nl/uitleg-trl/uitleg-trl/) and Amsterdam. At the start of the project, use of MICP to stabilize quay walls was at TRL level 5-6 (prototype tested under relevant conditions). Our goal is to take this technology to level TRL 7: prototype tested under operational conditions. This requires complex major technology development, which is only feasible through stepwise implementation. Thus, the project has multiple stages; including:

Proposal stage:

- We proposed consideration of MICP to the City of Amsterdam. Using in situ soil biology to stabilize technical structures such as quay walls is innovative and differs significantly from the ‘proven and trusted’ geotechnical solutions (using concrete and steel);
- When our proposal was accepted, we proceeded to:

Feasibility stage

- Conceptual feasibility assessment; in which geotechnical parameters that need to be improved to enhance quay wall stability were identified;
- Laboratory tests for proof concept and to determine optimal recipes;
- Numerical geotechnical modelling to determine the target cementation level and dimensions;
- Feasibility Report and business case analyses & proposal for field scale pilot
- When the feasibility of the project is accepted, we will proceed to:

Field scale pilot

- Select location for pilot;
- Fine-tune pilot design &Implement pilot
- Final Report

Feasibility stage

During the feasibility stage, testing of the MICP process on samples from Amsterdam quay fill showed that MICP can modify the properties of this fill / soil material and holds promise to

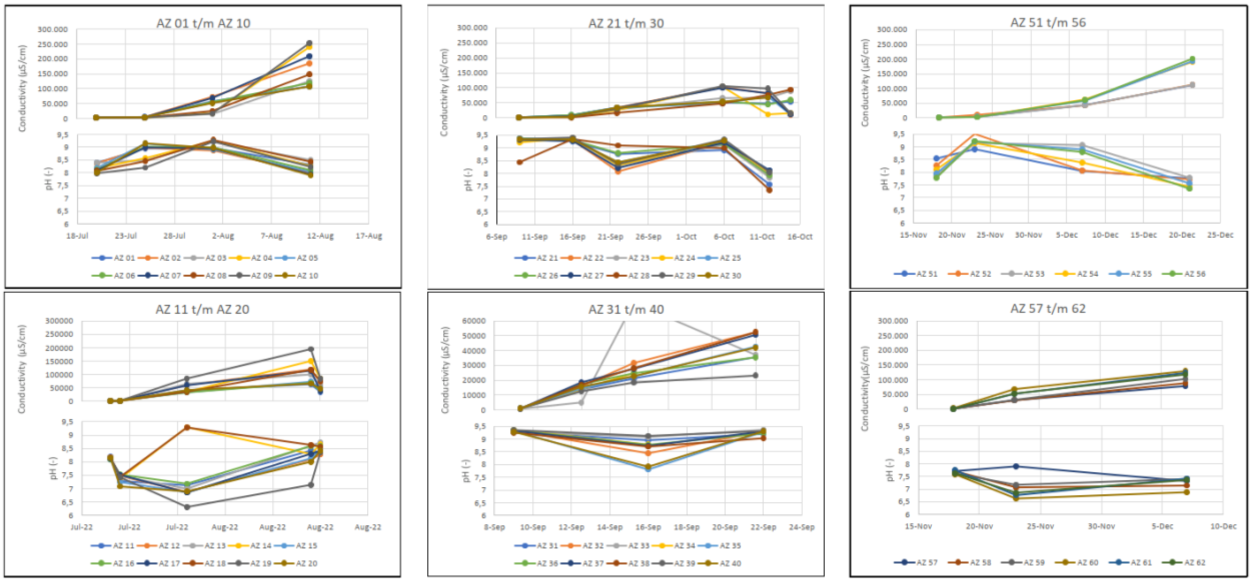


Figure 2. pH & conductivity during Amsterdam column tests

pH& EC measured on effluent of the column tests using a Hanna Instruments Bench Meter, HI5222 (pH/ISE/EC/Temperature)

improve longevity of quay walls. Figure 2 shows the effect of MICP treatment on the pH and electrical conductivity of the soil taken from behind the quay wall and Table 1 shows the effect of MICP treatment on the unconfined compressive strength (UCS) of treated samples). UCS was measured using a Gilson Pocket Penetrometer HM500 after air-drying the specimen, when necessary equipped with a modified (smaller) tip. Measurements were done in triplicate at different spots on each specimen. The average of the three measurements is reported as the strength of the sample.

While the laboratory testing was promising, implementation of a pilot test at an existing quay wall involves many uncertainties regarding the MICP process, and the effect of geotechnical parameters on quay wall stability. Therefore, using the Stage Gate decision model (AACE, 1958), it was concluded that the 'gate' between 'Feasibility' stage' and 'Field Scale Pilot' stage required further assessment, so a new stage, the "Detailed Design" stage was introduced.

Table 1. Estimated input parameters for bio-cemented sand to be used for numerical simulations using a linear elastic, perfectly plastic material model with a Mohr-Coulomb failure criterion

Parameter	Unit					
CaCO3%	[% dry weight]	0	1	2	3	5
dry unit weight	$[kN/m^3]$	15.00	15.15	15.30	15.45	15.75
solid unit weight	$[kN/m^3]$	26.5	26.5	26.5	26.5	26.5
void ratio	[-]	0.77	0.75	0.73	0.72	0.68
porosity	[-]	0.43	0.43	0.42	0.42	0.41
saturated unit weight	$[kN/m^3]$	19.3	19.4	19.5	19.6	19.8
Vs	[m/s]	130	230	330	430	630

Parameter	Unit					
CaCO3%	[% dry weight]	0	1	2	3	5
Gmax	[MPa]	25	80	167	286	625
nu	[-]	0.2	0.2	0.2	0.2	0.2
Eur	[MPa]	61	192	400	686	1500
E50	[MPa]	20	64	133	229	500
Peak Friction Angle	[o]	30	31	32	33	35
Cohesion	$[kN/m^2]$	0	5	11	21	52

Data is based on De Jong, JT, and M.G. Gomez,2022 and van Paassen, LA, 2010)

Detailed Design phase

To address the uncertainties identified during the feasibility stage, a detailed design stage was added to the evaluation process. This stage consisted of:

- Review what kind of fill material / soil is present (in general) behind the Amsterdam quay walls

- Review which types of fill/soil behind the quay walls are suited for MICP treatment
- If a sufficient portion of the quay walls have suitable fill, select a 'typical' location to obtain samples pf representative fill for laboratory testing (a 'sufficient portion' is not precisely defined, but must be enough to warrant further research into the feasibility for the Amsterdam quay walls).
- Run column tests and geotechnical tests (DS-tests) on samples to determine the relation between treatment and modification of geotechnical parameters;
- Run geotechnical model calculations (Plaxis 2D) to calculate anticipated effects of stress(-reduction) on the quay wall through application of MICP.

Estimates of effects of MICP on geotechnical parameters were listed in Table 1, based on literature review (DeJong et al, 2022, Van Paassen et al 2010). These values were used as modified input into a series of initial 2D Plaxis models of cross sections through typical Amsterdam quays. As a result of this modelling, we concluded that MICP can beneficially modify the geomechanical behaviour of soils behind Amsterdam quays to reduce the stress on the quays.

In general terms, MICP causes the soil to act more as a 'solid' block of cemented material in which the vertical loads exerted by pavement, fill and traffic (parked and moving) are conducted more in the vertical direction into the foundations and less in the horizontal direction, thus reducing the stress on the quay walls. The model calculations show that the amount of reduction of horizontal stress depends mostly on the configuration of the cemented body of soil and less on the degree of cementation in that body. Calculations also show that soil stratification, when layers of clay and/or peat would be present, could have a detrimental effect on the strain reduction caused by MICP. The Plaxis 2D model was employed for several relevant MICP improvement scenario's, based on an exemplar for an existing Amsterdam quay wall (Singel reach SIN0202). For each scenario, the calculated maximum horizontal displacement were of the quay resulting from prolonged vertical

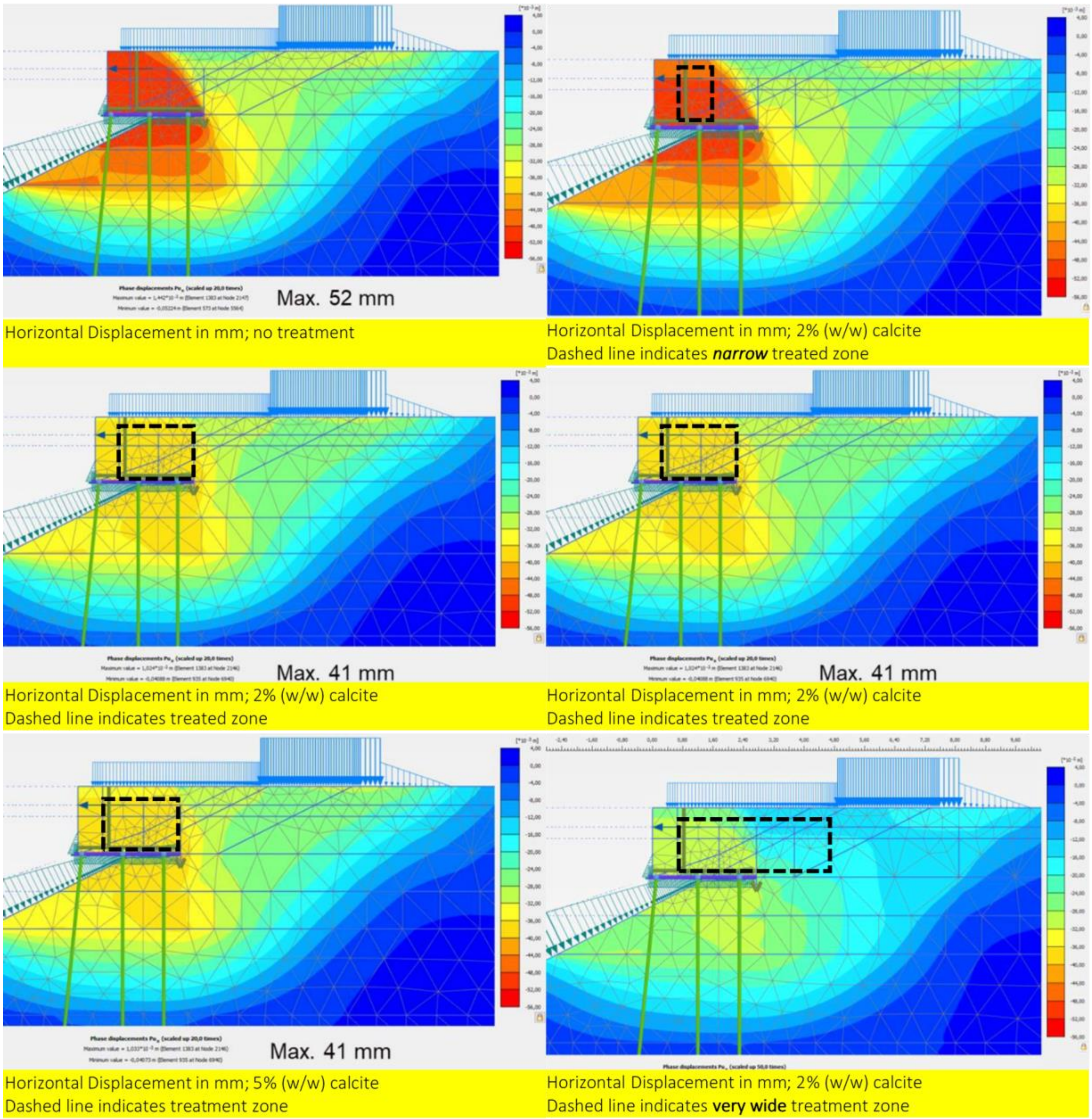
Table 2. UCS* after MICP treatment

Test	Calcite aim (w/w)	UCS (kg/cm2)	UCS (kg/cm2)	UCS (kg/cm2)	Av. UCS (kg/cm2)	Av. UCS (kPa)
AZ 33	1%	0,25	0,5	-	0,38	37
AZ 36	1%	0,5	-	-	0,5	49
AZ 38	1%	0,75	-	-	0,75	74
AZ 23	1%	1	1	-	1	98
AZ 28	1%	1,25	1	-	1,13	110
AZ 16	1%	1,25	-	-	1,25	123
AZ 13	1%	1,25	1,5	-	1,38	135
AZ 03	1%	2	1,5	1	1,5	147
AZ 08	1%	1,25	1,75	-	1,5	147
AZ 01	1%	1,5	1,75	-	1,63	159
AZ 06	1%	2	1,75	-	1,88	184
AZ 26	1%	3,5	2,5	-	3	294
AZ 21	1%	4,5	4,5	-	4,5	441
AZ 58	2%	0	0	0,25	0,08	8
AZ 34	2%	0,25	0,25	-	0,25	25
AZ 57	2%	0,25	0,25	0,25	0,25	25
AZ 39	2%	0,25	0,5	-	0,38	37
AZ 59	2%	0,5	0,5	0,25	0,42	41
AZ 61	2%	0,4	0,4	0,5	0,43	42
AZ 02	2%	0,5	0,5	-	0,5	49
AZ 30	2%	0,75	0,25	-	0,5	49
AZ 35	2%	0,5	-	-	0,5	49

Test	Calcite aim (w/w)	UCS (kg/cm2)	UCS (kg/cm2)	UCS (kg/cm2)	Av. UCS (kg/cm2)	Av. UCS (kPa)
AZ 53	2%	0,5	0,5	0,5	0,5	49
AZ 60	2%	0,5	0,5	0,5	0,5	49
AZ 51	2%	0,75	0,75	0,5	0,67	65
AZ 55	2%	0,5	0,75	0,75	0,67	65
AZ 56	2%	1	0,75	0,25	0,67	65
AZ 14	2%	0,75	0,75	-	0,75	74
AZ 52	2%	0,75	0,75	0,75	0,75	74
AZ 22	2%	0,75	1	-	0,88	86
AZ 25	2%	1	0,75	-	0,88	86
AZ 62	2%	1	0,5	1,2	0,9	88
AZ 12	2%	1,5	0,75	-	1,13	110
AZ 19	2%	1	1,25	-	1,13	110
AZ 54	2%	1,5	1	1	1,17	114
AZ 15	2%	1	1,75	-	1,38	135
AZ 24	2%	1,25	1,5	-	1,38	135
AZ 29	2%	1,75	1,25	-	1,5	147
AZ 04	2%	1,5	1,75	-	1,63	159
AZ 10	2%	1,5	1,75	-	1,63	159
AZ 07	2%	1,5	1,5	3,5	2,17	212
AZ 05	2%	2	3	-	2,5	245
AZ 27	2%	2,5	3	-	2,75	270
AZ 09	2%	2,5	3,5	-	3	294

*: UCS was measured after air-drying of each test using a Gilson Pocket Penetrometer HM500, when necessary equipped with a modified (smaller) tip. Measurements were done in triplicate at different spots on each sample. The average of the three measurements is considered representative for the strength of the sample

loading on the quay were plotted. The results show that the width of the treated zone is the most critical parameter to consider. The level of BISI cementation is less relevant. The cause for this



The model runs depicted on the left show the horizontal displacement for: No treatment, treatment to 2% (w/w) calcite and treatment to 5% (w/w) calcite. The effect of treatment is clear, the difference between 2% and 5% calcite is negligible.	The model runs depicted on the right show the horizontal displacement calculated for treatment to 2% (w/w) calcite over widths: **narrow**: 51 mm displacement: effect not significant; **construction width**; 41 mm displacement; **Very wide** (quay + parking): 25 mm displacement. The effect of treatment width is clear

The blue vertical arrows indicate static surface load distribution (parked bikes & cars & trees on the outer part, moving traffic on the quay road and pedestrian space on the inland edge). The vertical scale is from +4 mm (inland) to -56 mm displacement (outward towards the canal)

Figure 3. Plaxis analyses of anticipated effects of BISI treatment on quay walls

phenomenon is that at just 2% calcite the treated fill mass acts as 'one solid block' that transmits the vertical loads to the foundation.
When a narrow block is assumed, the cementation has little to no effect on the strain on the quay wall. When a wider block is assumed, the block is better capable of transmitting forces down into the foundation. Figure 3 illustrates the results of the Plaxis analyses.

Review of BISI-treatable Amsterdam quay soil types
The next step in the process was to review the types of soil present behind the quays of Amsterdam and classify these as to their (likely) amenability to successful MICP treatment. Tests were done in open top vertical percolation columns using biostimulation of the indigenous microbes present in the sample. Thirteen (13) soil types were identified based on a search of the BRO database.

Nine (9) were evaluated and of these, 3 are qualified as 'likely amenable to MICP treatment' (Table 3). The database was searched for presence of these soil types in the soils directly behind the quay walls, above the wooden foundation boarding. Seven quays at the locations identified in Figure 4 and listed in Table 4 were identified as having ample information available on the soil/fill behind the quay walls to merit evaluation for MICP improvement. Figure 4 and listed in Table 4

Table 3. Amenability of fill types for BISI based strength improvement

Fill	estimated score	max. score	Anticipated effectiveness Calcite cementation
Sand	95%	100%	Highly effective
Sand w. pebbles	95%	100%	Highly effective
Silty sand	85%	95%	Silty sand (< 15% fines) is very well treatable, but treatment effectivity decreases as the larger number of particles requires more cementing bonds (= more calcite) to create small strain stiffness; and the permeability is lower, making application more cumbersome.
Very silty sand	50%	70%	Very silty sand (> 15% fines) is difficult to treat effectively, as the very large number of particles requires much more cementing bonds (= more calcite) to create small strain stiffness; and the permeability is much lower, making application more cumbersome.
Sandy silt	20%	30%	Silt containing a small fraction of sand will behave like silt, which is very difficult to treat effectively
Very sandy clay	10%	10%	When clay content exceeds 20%: BISI not applicable
Clayey sand	5%	20%	Depends strongly on clay content. Clayey sand contains (by definition) 5 – 8% clay. At 5% clay treatability is expected to be similar to silty sand; at more that 15% clay, treatability is unlikely.
silt	20%	40%	Material containing 80% or more particles < 63 µm, is unlikely to be effectively treatable using BISI..
Slightly sandy Peat	10%	10%	Soil consisting predominantly of peat and/or clay is not considered treatable using BISI. We expect that a thin peat of clay layer will not significantly affect the BISI treatment of the sand layers above and below; and thus not impact treatability (unless the clay or peat layer would constitute a failure plane)

were identified as having ample information available on the soil/fill behind the quay walls to

Table 4. Soil / fill material in top 2 m below surface in BRO database

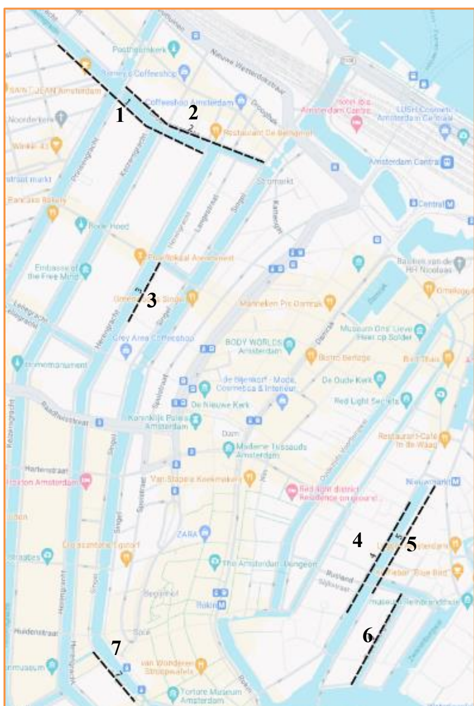
	Sand / Sand with gravel	Slightly to Very Silty Sand	Silt, peat or clay
Brouwersgracht Zuid	59%	35%	6%
Brouwersgracht Noord	85%	1%	14%
Herengracht	87%	8%	5%
Kloveniersbrugwal West	90%	5%	5%
Kloveniersbrugwal Oost	85%	6%	8%
Groenbrugwal	26%	71%	4%
Singel	23%	57%	20%

merit evaluation for MICP improvement.
The amount of different types of fill behind the quay walls varies (Table 4). For each of the 113 borings (data point) along these seven canals, we analysed which soils types are present in the top 2 meters. Combining that with the likelihood of successful MICP treatment, we calculated a

weighted average of feasibility factors (the soil type, silt content and quantities of sandy, silty and other materials at each location). As shown in Figure 5, approximately 66% of the data points resulted in a score of 80% or higher, indicating BISI (the MICP process) can likely be deployed successfully. In the other 34% of the data points, the quantity of silt, clay or peat is higher, resulting in a lower probability of successful BISI application. The impact of silt content on the feasibility of BISI (MICP) treatment is critical.

To assess the potential for BISI along a full reach of quay wall (a 'reach' is defined as a section of quay between two bridges, including the rising part of the quay leading to the bridge, but excluding the bridge itself), spatial variation of soil needs to be assessed. For each of the seven quays, we analysed the scores for distance-dependent variance along the quay for lengths of 5 -200 m to calculate the maximum probable length of successful BISI application. As shown in figure 6 for exemplar case of Brouwersgracht Noord, the score is 95% for 50 m, 86% for 100 m and 72% for 200 m.

Figure 7 presents the results of analysing this for all seven quays reviewed in this study. In one case (Singel) BISI is not likely to be successful, in the case of Groenburgwal, Herengracht and Kloveniersburgwal Oost, BISI is likely to be successful for reaches up to 140 m, for the other three cases, BISI is likely to be successful for the entire reach.



Quay names

1 = Brouwersgracht zuid;
2 = Brouwersgracht noord;
3 = Herengracht;
4 = Kloveniersbrugwal west;
5 = Kloveniersbrugwal oost;
6 = Groenbrugwal;
7 = Singel

Figure 4. Amsterdam quays with ample soil data

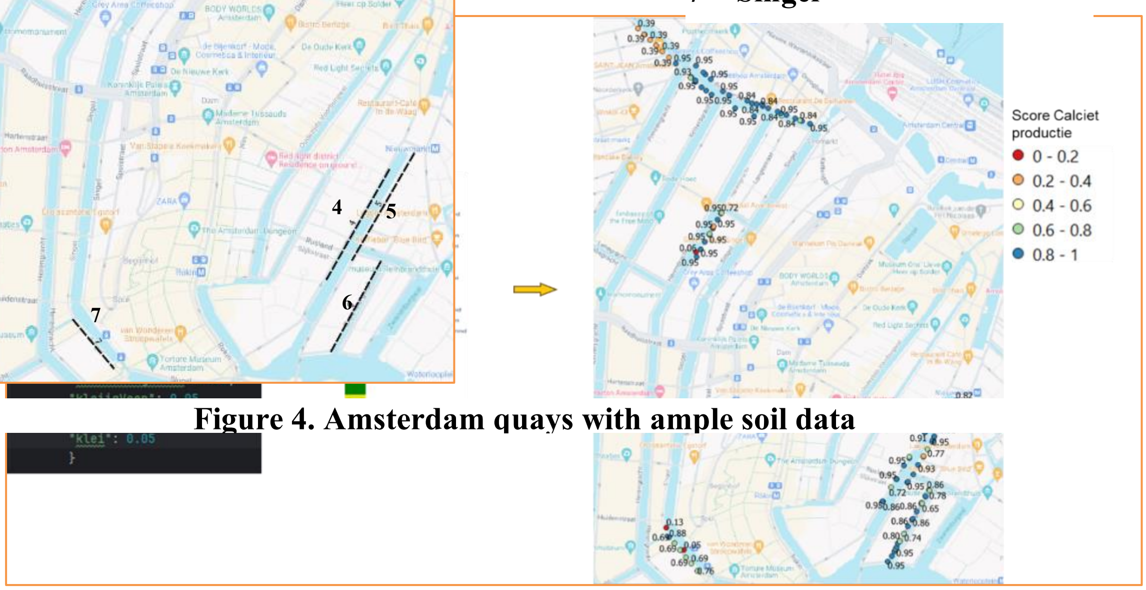


Figure 5. Illustration of likelihood of effective MICP treatment of top 2 m fill. Based on a score per soil type (left block) we calculated an average score. The result was plotted on a site map.

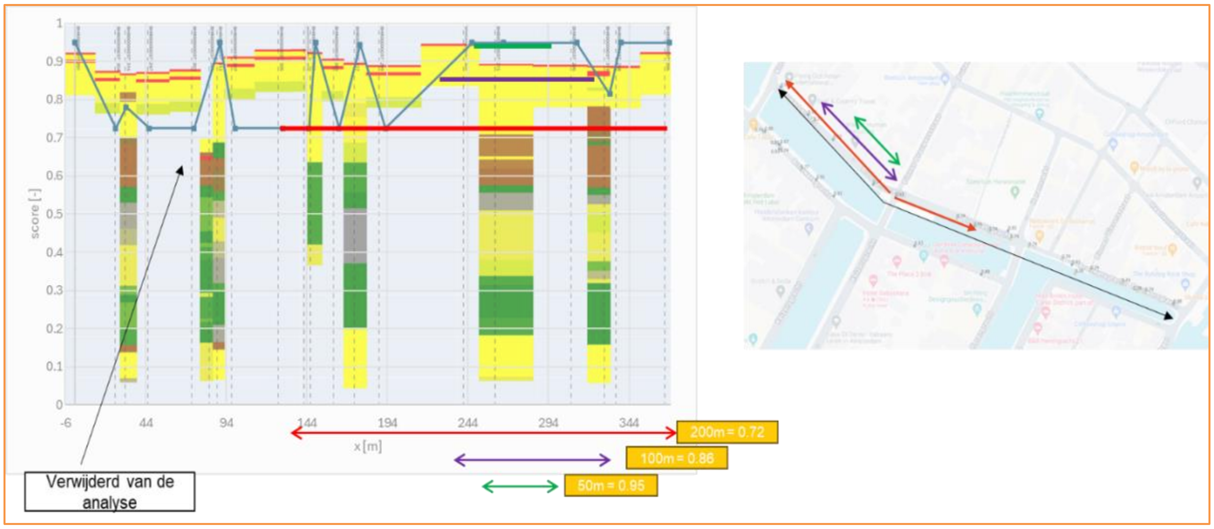


Figure 6. Illustration of likely effective treatment over lengths of quays. On the left is a cross section of the soil profile behind the quay projected behind a graph presenting the given score per borehole profile (counting only the top 2m). The horizontal lines (red, blue, and green show the given score for a certain length of quay wall defined by the score of the most critical soil profile within that length. On the right is the projection of the three lengths of quay in a top-view.

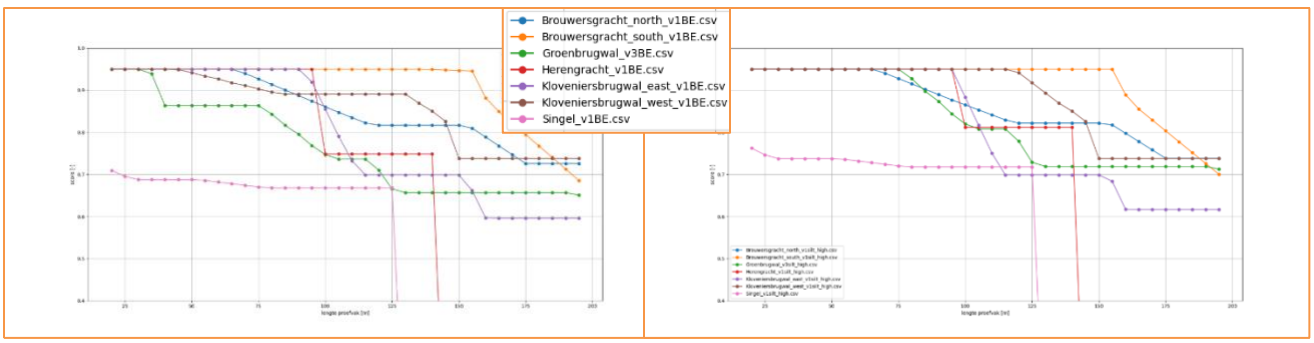


Figure 7. Illustration of likely effective treatment per m for the 7 quays. Left: representation based on the estimated score; Right: representation based on the slightly higher score for silty sand

We conclude that:

- The analyses did not evaluate for presence of a silt or clayey layer of limited thickness (which could be detrimental to spatial distribution of the calcite formation); typically, this can be avoided by multi-layer injection;
- The effect of silt content in the typically sandy fill is critical and merits further evaluation for the Amsterdam case: in many cases, a patch of more silty material could still be effectively treated by adapting the treatment system design and increasing the amount of precipitated calcite;
- The analyses is limited to the upper 2 m of fill/soil, which is normal for the typical reaches of quays in Amsterdam. In cases where the quay is higher (e.g. near bridges), these analyses did not incorporate the deeper material behind the quay wall.

Ecology and Biodiversity

The trees along the Amsterdam canals are of particularly high value to the 'appearance' and the 'look and feel' of the canals and are essential for the historic value of the canals and quays. The quay walls themselves form a unique and rare ecosystem on which many forms of small living plants and animals thrive. Reviewing potential effects of MICP on ecology (in particular, but not limited to, the trees as well as biodiversity is in progress;

Feasibility analysis of the business case

An initial evaluation of the business case estimates the costs of BISI treatment of Amsterdam quay walls (increasing longevity by 30 years) at € 7.500 to € 10.000 per meter of quay wall. Implementing a permanent solution (full reconstruction, leading to longevity of 100+ years) is estimated at € 40.000 per meter. This does not take 'non-monetary' aspects into account, such as the vast difference in impact on 'city life' and well being of residents between in situ soil treatment which does not require closure of the roads on the quays, and full reconstruction, which will close access to the quay for many months and require massive transport and bulky equipment.

CONCLUSIONS

The MICP process is well documented in literature. Documented practical applications of MICP in full operational conditions are rare to non-existent. The quays in Amsterdam are of variable stability; some are stable, some require measures to improve stability to increase life-expectancy to 30+ years and some require urgent intervention to guarantee safety. We proposed BISI to increase longevity to 30+ years by implementing MICP. MICP is highly innovative in this context, there are no reference cases. Therefore, a stepwise approach is necessary to demonstrate safe applicability in the specific context of the Amsterdam quay walls and take the (application) of the technology from TRL 5-6 to 7. We have shown that:

- The effect of MICP on the quay wall stability is partially related to the level of cementation; more cementation than the minimum to achieve the desired result does not further improve stability;
- The spatial distribution of treatment has a strong effect on the resulting improvement of stability. Treating a narrow zone behind the quay walls does not improve stability. Treating the material behind the quay walls over the full width of the foundation construction yields sufficient stability. Treating a wider zone improves stability further;
- MICP treatment improves stability of the quay walls by directing horizontal forces in the material behind the quay walls downward, into the foundation.
- Assessment and statistical evaluation of the type of material behind the quay walls (sand/ silt/clay/peat/waste) demonstrated that 75% to 95% of these materials are amenable to MICP treatment.

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