UNSUITABLE TO SUITABLE: A CHANGE IN THE RECLAMATION DESIGN PARADIGM

The availability of suitable sand has become a limiting factor in the development of many ambitious reclamation projects, making the reuse of existing, less suitable materials a critical solution. This subject has been given broader international attention in the past years driven by the shortage of sand resources and by the desire for a more circular society where waste does not exist. So far, only a few examples exist of islands that have been constructed with fine silty or even clayey sediment. In this context, the reclamation with sediments must evolve from an exceptional case requiring special considerations, to a common practice. To favour this practice, an integrated framework is needed where the concepts of suitable and unsuitable are redefined.

Suitable versus unsuitable: the stated view

Reclamation projects are defined as the construction of new land over existing water bodies (seas, rivers, lakes or oceans). In contrast to conventional earth fill and backfill works used in the construction of embankments or backfill of an excavated area, the fill material is placed in layers on a water-content controlled environment, using the Proctor criteria as a guide. The fill is placed at its optimum water content and compaction is done for every layer.

In reclamation works, the fill is formed in a water-dominated environment, the compaction conditions cannot be controlled and the optimum water content concept is not applicable. The fill is placed in a few layers (if deemed necessary) and soil compaction is performed, if required after fill placement is completed.

Within this context, the concept of suitable and unsuitable materials emerged. Suitable materials are defined as materials that, placed in a water-dominated environment, do not experience a significant segregation, exhibit a rapid settlement and develop a significant strength in a relatively short time, which enables more or less immediate accessibility. Unsuitable materials, on the other hand, are materials that require longer time to settle, are prone to segregate and whose strength and compressibility develop slowly over time. Those kind of fill areas cannot be accessed without additional measures to be taken.

The difference between these two concepts is reflected in the different timeline representations depicted in Figure 1, where the settling process is represented in the case of suitable and unsuitable materials.

Examples of suitable soils are granular materials, such as gravel or sand, with a limited amount of fines. Unsuitable soils include fine-grained materials, such as clay and silt, or sandy soils with high fine content. The boundary between suitable and unsuitable soils is drawn by the acceptance criteria for the fill material, defined through the fine content and the mean particle size D50 (Figure 2). Figure 3 shows the transition between suitable and unsuitable materials and the gradual change in the relevant engineering properties for reclamation design as strength, compressibility and permeability.

The left side of the figure represents granular soils, such as clean sands and gravels. These materials are characterised by high strength, low compressibility and high permeability. The right side of the figure represents the materials with a significant amount of fines, consisting of clays and silty clays. These materials are characterised by low bearing capacity, high compressibility and low to very low permeability. The transition between these materials consists of a mixture of both fractions. Geotechnical properties for the resulting composite mix depend on the main fraction, varying from high to low strength, from low to high compressibility and from high to low permeability. This interpretation is reflected in Figre 3, which represents the study performed by Fan et al. (2023) regarding the compressibility and hydraulic conductivity of sand-silt tailings mixtures.

A change in the compressibility is observed for fine content above 15%, reflecting the effect of the fine soil fraction on the soil matrix behaviour. This value is in line with the boundary defined to distinguish suitable and unsuitable soils. For the hydraulic conductivity, this change is associated to a fine content around 40–50%.

Traditional and emerging paradigms

In a traditional reclamation design approach, the use of materials containing a significant amount of unsuitable soils is limited to a minimum. When this amount is higher than the acceptable quantity, it is segregated from the dredged soil and discarded as waste. In addition to the performance-related aspects, the environmental restrictions are minimal and the availability of suitable materials do not conform to a great limitation. In this view, suitable materials are sourced to comply with the materials specification and the performance criteria included in the basis of design. The following premises are recognised in this approach: 1) suitable materials are always available in close vicinity (either from a dedicated borrow area or in the parented dredge area); 2) waste is possible; and 3) the environmental and sustainable aspects are not a limiting factor.

In the traditional view, reclaiming land with sediments and fine-grained soils is considered as a special case and no standard practice is recognised. This is reflected in the structure adopted by the Hydraulic Fill Manual (Van 'T Hoff et al., 2012), aimed to guide the design and execution of reclamation projects to obtain optimal results. Aspects like availability of material, boundary conditions, dredging equipment and the functional and performance criteria for the reclamation fill are considered (Figure 4). In the proposed workflow, the use of fine-grained soils is considered as a "special fill" case (Section 9) requiring specific actions to mitigate "problematic" aspects.

Nowadays, obtaining suitable materials from a dedicated borrow area or extracting the suitable fraction from the existing materials in the associated dredge areas to be used as a source for reclamation fill is highly contingent. Sand utilisation has increased over the past

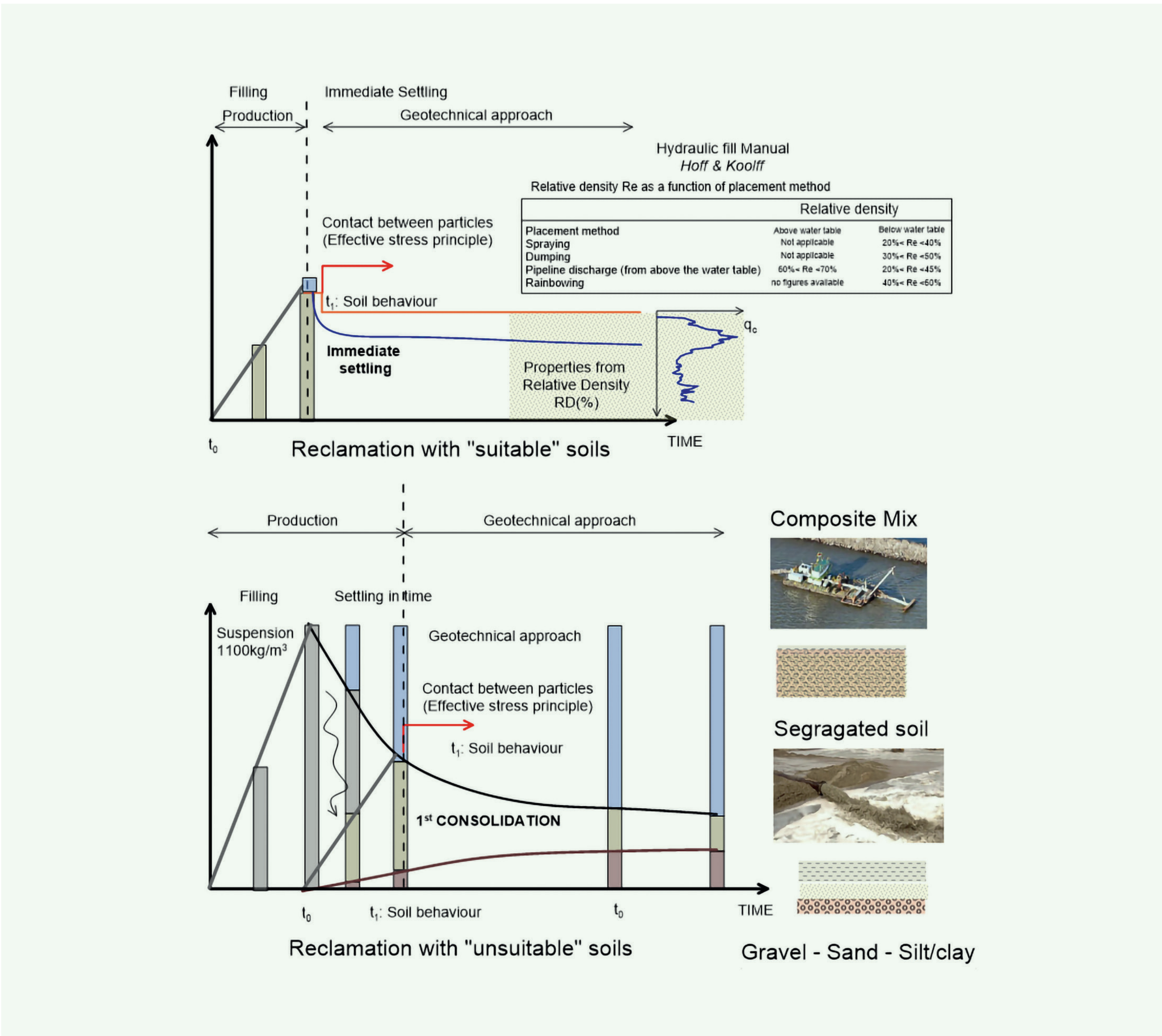

FIGURE 1

Timeline representation of the fill placement for "suitable" (above) and "unsuitable" soils (below) in a reclamation and settling process.

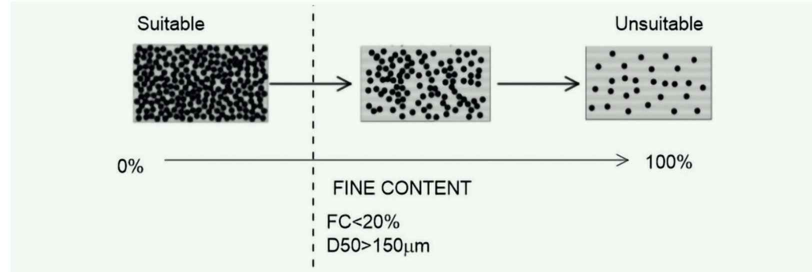

FIGURE 2

Fine content and D50 limits for suitable soils.

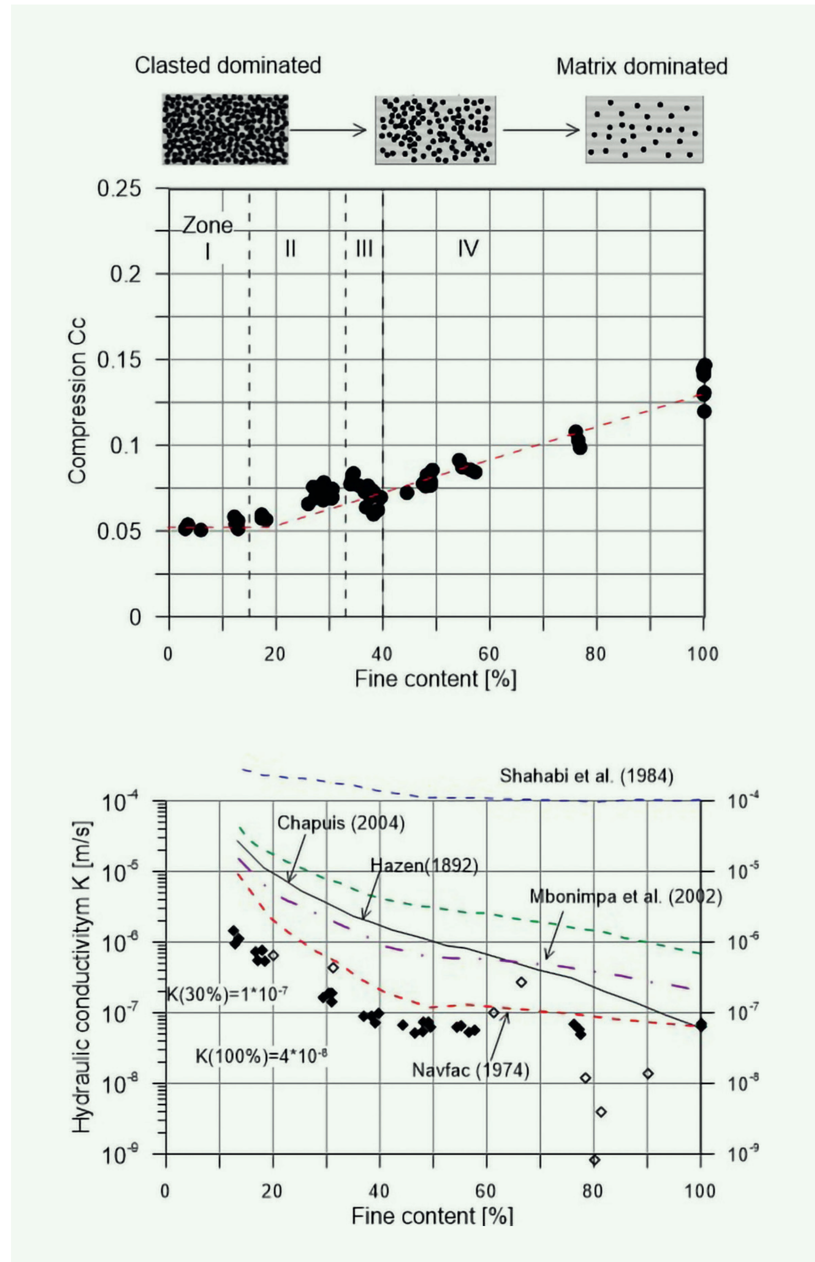

FIGURE 3

Compressibility and hydraulic conductivity for composite mix materials from sand-silt (Fan et al., 2023).

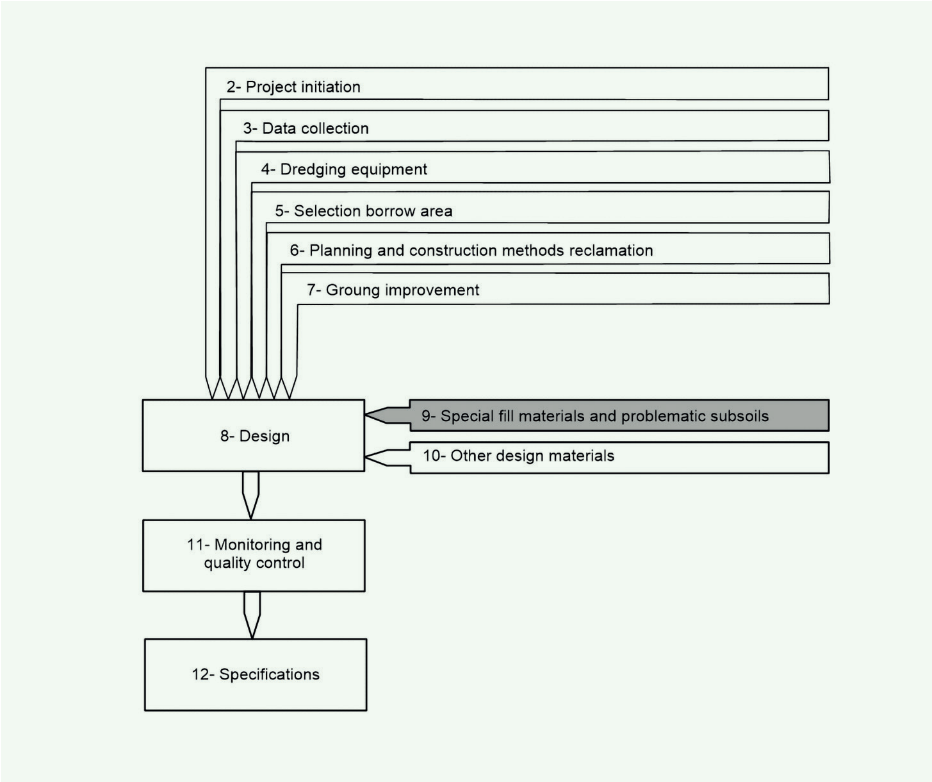

FIGURE 4

Workflow and setup to plan design and execution activities in reclamation projects (Van 't Hoff et al., 2012).

decades and is becoming scarce around the world (UNEP, 2022). Additionally, increasing environmental awareness around the world leads to more restrictions on sediment spills in waters as well as extracting sand from the seabed, which is harmful to marine ecosystems. The combination of scarcity of sand and turbidity (overflow) restrictions has led to the need of reusing "complex" types of materials in land reclamations.

The broader international attention given to this subject over the past years was driven by the shortage of sand resources and the desire for a more circular society where waste does not exist. So far, only a few examples exist of reclamations constructed with fine silty or even clayey sediment. Figure 5 presents a view of the Kalibaru project where high plasticity clays were used for the construction of new land for the port of Tanjung Priok, Jakarta, Indonesia.

In this context, the approach to land reclamation with sediments must evolve from being an exceptional case to become a common practice.

The changing process requires the review of legal and contractual aspects, and of several design paradigms related to engineering. Fundamentally, the design process should be turned around, the starting point should be the source material instead of the specifications for the reclamation. The following questions should be asked: What type of sediment is available? What needs to be done in the reclamation to turn it into land fit for purpose? The answers to these questions will directly influence the time required to finish a project, the work method, the equipment to be employed and the form of contract. In this new scenario, a significant transfer of time and costs from the dredging operations to the reclamation design and execution/ construction is to be expected.

Figure 6 represents two design workflows. The first one, named from performance to material, reflects the classic design approach where a suitable material is sourced to comply with the design and performance requirements of the project. Material specifications are included as part of the tender documents and production, cost and environmental aspects are all aspects left to the contractor. The available time for completion is determined by the employer and defined in relation to construction with suitable materials. Often the available time is already fairly limited and tight. Alternative to the former, a new design approach paradigm is nowadays more frequently used. This new approach, named from material to performance, considers the availability of materials together with environmental, production and legal aspects to deliver an adequate compliant product.

State-of-the-art, knowledge gap and engineering challenges

When looking into the available literature, it is apparent that the use of fine-grained soil has received quite some attention from several engineering perspectives. The impact of fines content on consolidation behaviour is investigated by Lipinski, Lupongo and others (Lipinski et al., 2017; Lupongo, 2009; Fan et al., 2021). The effect of ground improvement on the consolidation behaviour of fill materials has been researched by Chu et al. (2008). The corresponding costs of ground improvement methods are elaborated by Hazirbaba and Mughieda (2019). Modelling of large strain consolidation behaviour of (soft) soils is widely investigated (e.g. Gibson, 1967; Agapito and Bareither, 2018; de Lillis et al., 2020; Ito and Azam, 2013; Ahmed et al., 2023; Ni and Geng, 2022). Yao et al. (2002 propose a clear guide on numerical methods for modelling large-strain consolidation of soft soils. A way to numerically model consolidation including vertical drains is demonstrated by Nguyen (2019) and Ni and Geng (2022). The effect of consolidation of slurries is also widely investigated (e.g. Van Der Meulen et al., 2012; Chu et al., 2008; USACE, 2015; Lam, 2018; Ganesalingam, 2013).

The scientific field of dredging is widely researched as well. The effects of dredging work methods on soil properties relevant for consolidation are briefly elaborated by Van Rijn (2005) and USACE (2015) and the Hydraulic Fill Manual (Van 'T't Hoff et al., 2012). A very interesting guide to soil parameters depending on fine content and placing method is also included in the Spanish recommendations for maritime works (ROM 04).

Hydraulic dredging and the corresponding production rates for TSHDs and CSDs are widely researched by, for example, Vlasblom (2005), Wowtschuk (2016), Braaksma (2017), Schrieck (2021), Miedema (2006) and Salzmann et al. (1977). The effects of mechanical dredging and its associated production rate are elaborated by Vlasblom (2005), Van Rijn (2005) and USACE (2015).

Two main conclusions can be drawn from the review and the information available (see C. Smeenk, in prep):

- A lot of specific knowledge exists on dredging and its effect on consolidation parameters, dredging production, ground improvement efficiency and the costs of each project component. However, this knowledge is likely to stay in-house at dredging companies to maintain their competitive position in the market; and
- Little to no research is performed on the effects of dredging work methods on consolidation parameters, comparing hydraulic methods to mechanical methods. There seems to be a lot of understanding of both the dredging phase and the consolidation phase when considering land reclamations. However, the coupling between the dredging work methods and the consolidation behaviour of a fill is missing. No research is performed on the effect of dredging work methods on total project costs and duration.

Regarding these conclusions, the following is observed. The share of knowledge is of vital importance in the development of a new design paradigm where the use of fine-grained soils is treated within the main planning workflow and not as a collection of individual cases forming a side branch. Moreover, there is a need for research on the effect of dredging work methods on total project costs and duration, coupling the production phase to the consolidation behaviour of the fill.

To develop an integrated design approach between production and reclamation design,

The approach to land reclamation with sediments must become common practice.

the following engineering challenges are identified (C. Smeenk, in prep):

- What is the impact of mechanical and hydraulic dredging on the soil properties of dredged material relevant for the consolidation?
- What are the factors that impact the consolidation behaviour of soft soils in reclamation fill?

FIGURE 5

Kalibaru project. Construction of new land for the Kalibaru terminal in the port of Tanjung Priok, Jakarta, Indonesia.

- How can the dredging phase and the reclamation phase individually be related to project performance in terms of duration and costs?
- How can the dredging work method be coupled to consolidation behaviour in a model to evaluate the selection of the dredging work method against project performance in terms of duration and costs?
- What is the effect of increasing fines content on the most cost and time-efficient dredging work method in land reclamation projects?

Each of these questions needs to be answered for a specific context aiming to achieve the optimal project performance in terms of time and cost. Figure 7 presents a schematic view of the effect of segregation in the fill when placed with high-energy and low-energy methods. A high-energy method is presented at the top of the diagram, i.e. the fill is placed using landlines where gravel and sand materials are expected to settle close to the pipe while the finer fraction is settling at significantly longer distances. This is used when segregation is favoured to obtain the suitable part for high-strength structures, such as bunds or structural backfills. At the bottom of the diagram, the fill is placed using a low-energy method (a spray pontoon) aimed to minimise segregation and avoid the presence of fine ponds.

Requirements for an integrated approach

The backbone of this approach should be developed combining the geotechnical perspective with the operational dredging process point of view (from now on referred to as production aspects). The need for an integrated approach where different aspects can be rationally combined is required for the trade-off comparison between alternatives. Specific aspects, such as bulking and placement conditions can be incorporated as quantitative variables bridging the gap between both disciplines. However, the most important thing is a change in mindset related to the following aspects.

Reclamation related aspects

From the reclamation perspective, the following engineering aspects will require special attention (Figure 8):

Segregation and bulking

Segregation, if it occurs, will strongly affect the placement properties of the soil, for example, its compressibility and strength, and of course, its initial volume. The effect of segregation in a unitary volume is represented in Figure 9. The specific volume of a segregated material will reflect the bulking value for each independent fraction while the volume for a non-segregated material will reflect the compaction conditions of a composite mix.

Self-weight consolidation

There are many studies and methods developed for the description of the self-weight consolidation of fine-grained materials. In most cases, the proposed formulations are developed to describe the depositional process of one single layer and the solid fraction is assumed constant over the entire analysis.
Some modifications are required to apply these methods to the study of a reclamation process considering production rates and layer thickness. As a result of these models the initial volume, water content and strength profiles for the topsoil would be estimated.

Settling columns appear as the most adequate test for calibration purposes and for that its execution will need to become a common requirement as part of the tender phase.

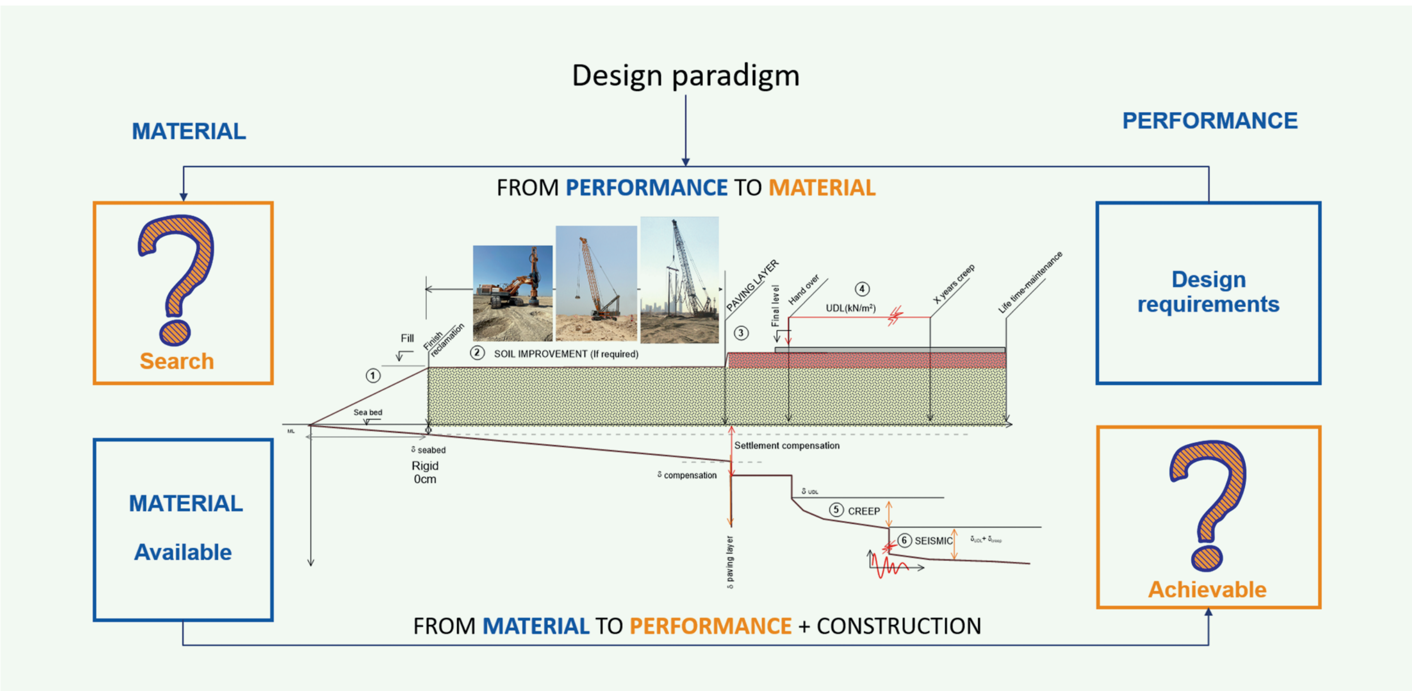

FIGURE 6

Design paradigms. The traditional approach implemented from performance to material (above) and the emerging view (below), where the design is implemented from the material availability and performance is considered as an adequate result of the construction and soil improvement.

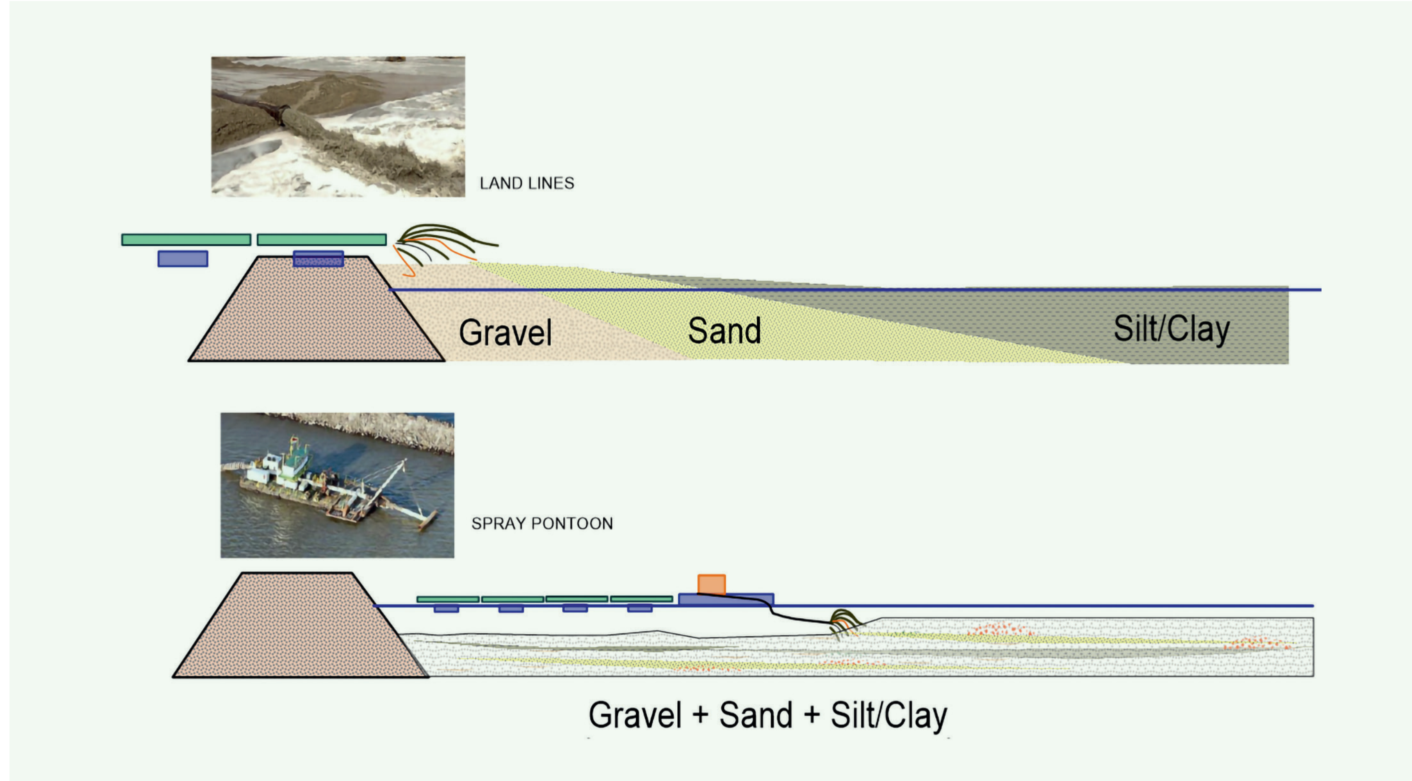

FIGURE 7

Placement with high-energy and low-energy methods. Above: landlines are used to favour segregation and maximise production rates. Below: spray pontoon is used to minimise segregation, avoid the formation of fine ponds and obtain a more homogeneous fill.

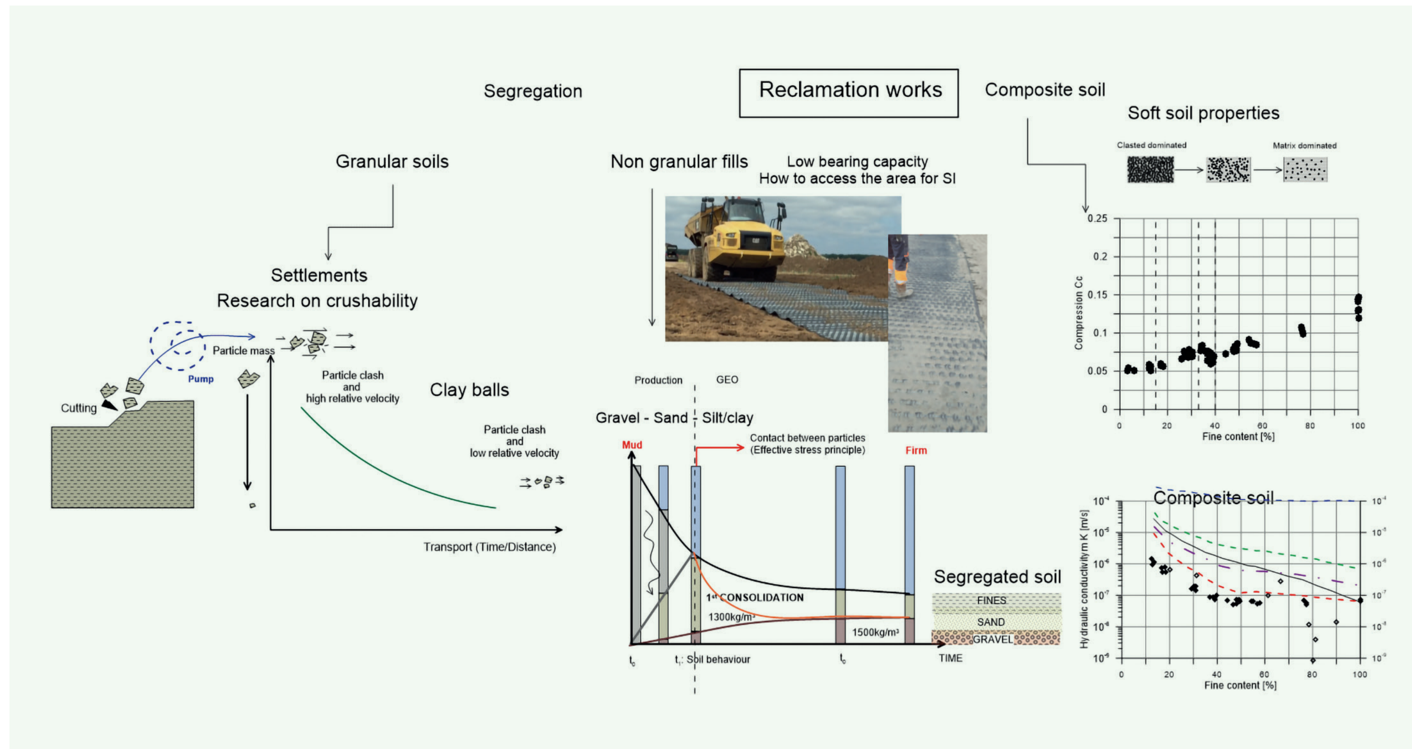

FIGURE 8

Reclamation engineering aspects that require attention for developing an integrated approach.

Figure 10 shows the results of a one dimensional settling column model performed by Smeek (in preparation). He adapted the formulation proposed by Gibson to incorporate the placement of layers at a certain rate, defined by the production aspects. The calibration of the model is done based on settling column tests demonstrating their relevance for the study of these problems at a laboratory scale.

Clay balls

Hard and firm clays tend to form balls during cutting. During hydraulic transportation, these balls tend to degrade but many will "survive" and will deposit in the form of a ball in the reclamation. Figure 11 shows the clay balls and sand fraction deposited close to the outfall in the reclamation.

The clay fraction in these clay balls will settle fast and its compression properties will reflect its in situ condition. When compared to the slurry fraction, clay balls will behave as a granular material in terms of settling time and consolidation. The work from van Beek (2023) can be considered as reference study in the field of clay ball formation and clay lump erosion in hydraulic dredge pipes.

Fill properties and soil improvement methods

The estimation of the engineering properties of the fill will be crucial for the analysis of its performance and the selection of the most adequate soil improvement method to be used.

Capping methods

After the self-weight consolidation of the fill material is completed, a capping layer or reinforced construction will be placed. This capping layer or reinforced construction is needed to provide sufficient bearing capacity for the ground improvement (GI) equipment to access the reclamation. The capping layer can be placed with low-energy methods (e.g., spray pontoon) in the form of a diffusor on top of the soft fill material or other methods can be used. By doing this, no instabilities will be caused by placing the capping layer. Alternatively, the formation of a crust can be favoured to "reinforce" the topsoil providing the required strength for the access of the required (GI) equipment. Figure 12 shows examples of capping with a sand cover layer and crust formation used in the Fehmarn Belt project.

Production related aspects

From the production perspective, aspects like the production rate, production duration and production costs are to be considered for the two main dredging work methods: hydraulic and mechanical dredging. Hydraulic dredging is often considered to be the fastest and cheapest dredging method. However, the counterpart is that the dredged soil is placed with a significant amount of water resulting in a fill material characterised by low hydraulic conductivity and high compressibility. The consequence of this is that the fill will require a long consolidation time or a costly ground improvement method in order to meet the design requirements. Another aspect of hydraulic dredging of soft soils is the high bulking factor.

Mechanical dredging is often considered to be more expensive and more time consuming than hydraulic dredging. However, the advantage of the mechanical method is that it preserves more the in-situ properties of the soil. This is because the material is excavated from the seabed by the bucket and a minimum of water is added. The resulting fill material is characterised by a lower water content, a higher density, a lower compressibility and higher bearing capacity compared to the material produced by hydraulic dredging. This will lead to relatively shorter consolidation times and a reduction in the amount of ground improvement required to meet the design requirements. Bulking factors are also much lower.

The above considerations of the different dredging methods illustrate that the fastest and cheapest dredging method may not necessarily lead to the fastest and cheapest consolidation phase, especially when using soils with high fine content. This makes it evident that a trade-off exists between total project costs and duration, which is governed by the chosen dredging work method. This trade-off element comes

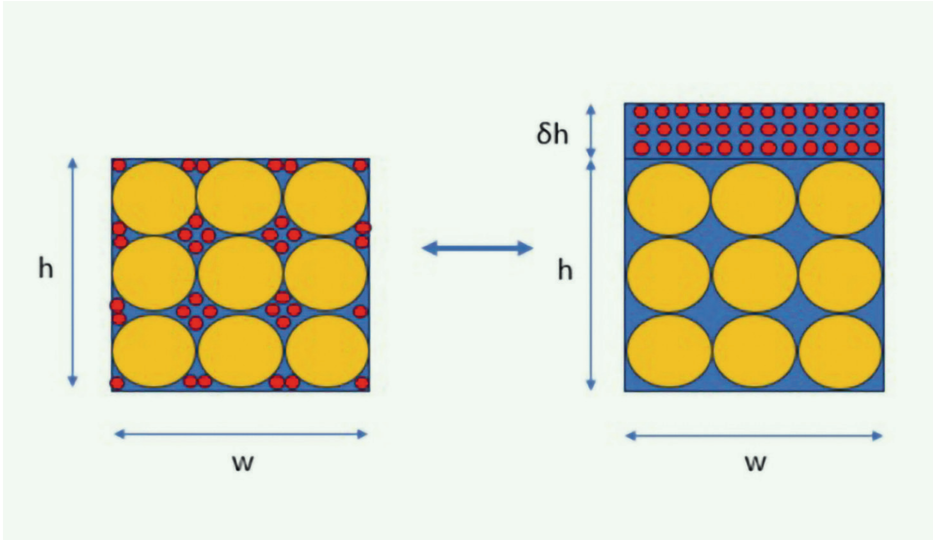

FIGURE 9
Specific volume for a segregated and non-segregated soil.

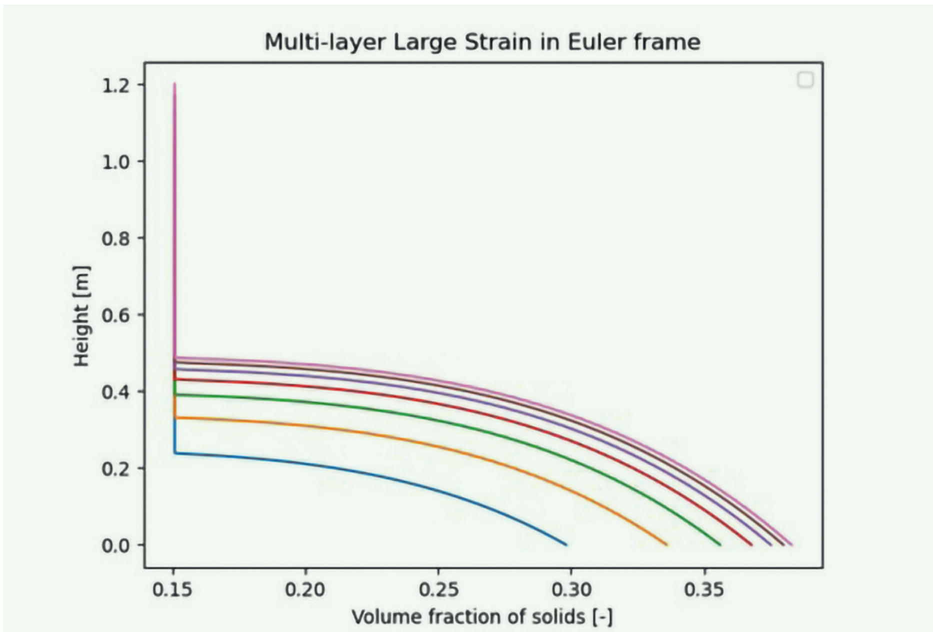

FIGURE 10
Solid fraction profile for a multi-layered settling column test.

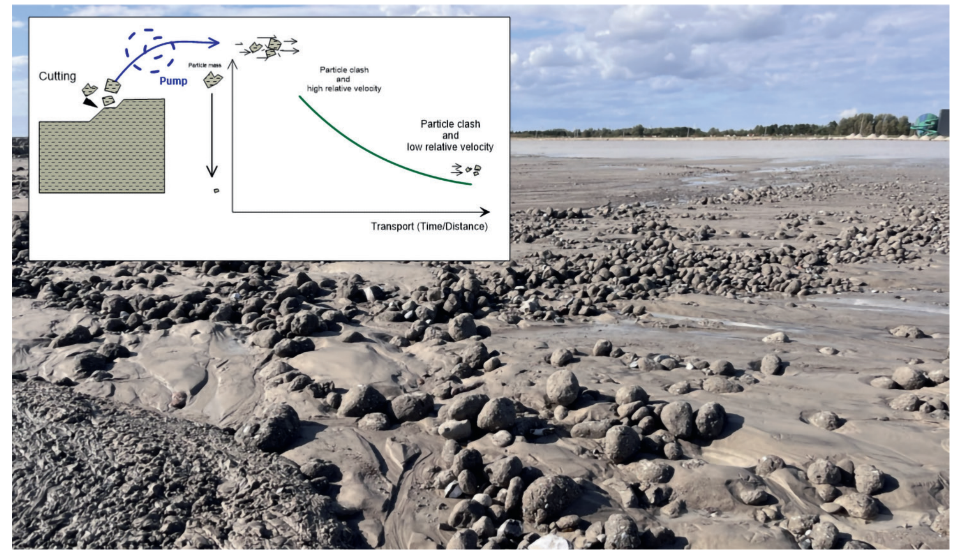

FIGURE 11
Clay balls and sand fraction deposited in the reclamation close to the pipe outfall.

FIGURE 12
Capping examples. Placement of a sand layer and crust formation at Fehmarn Belt project.

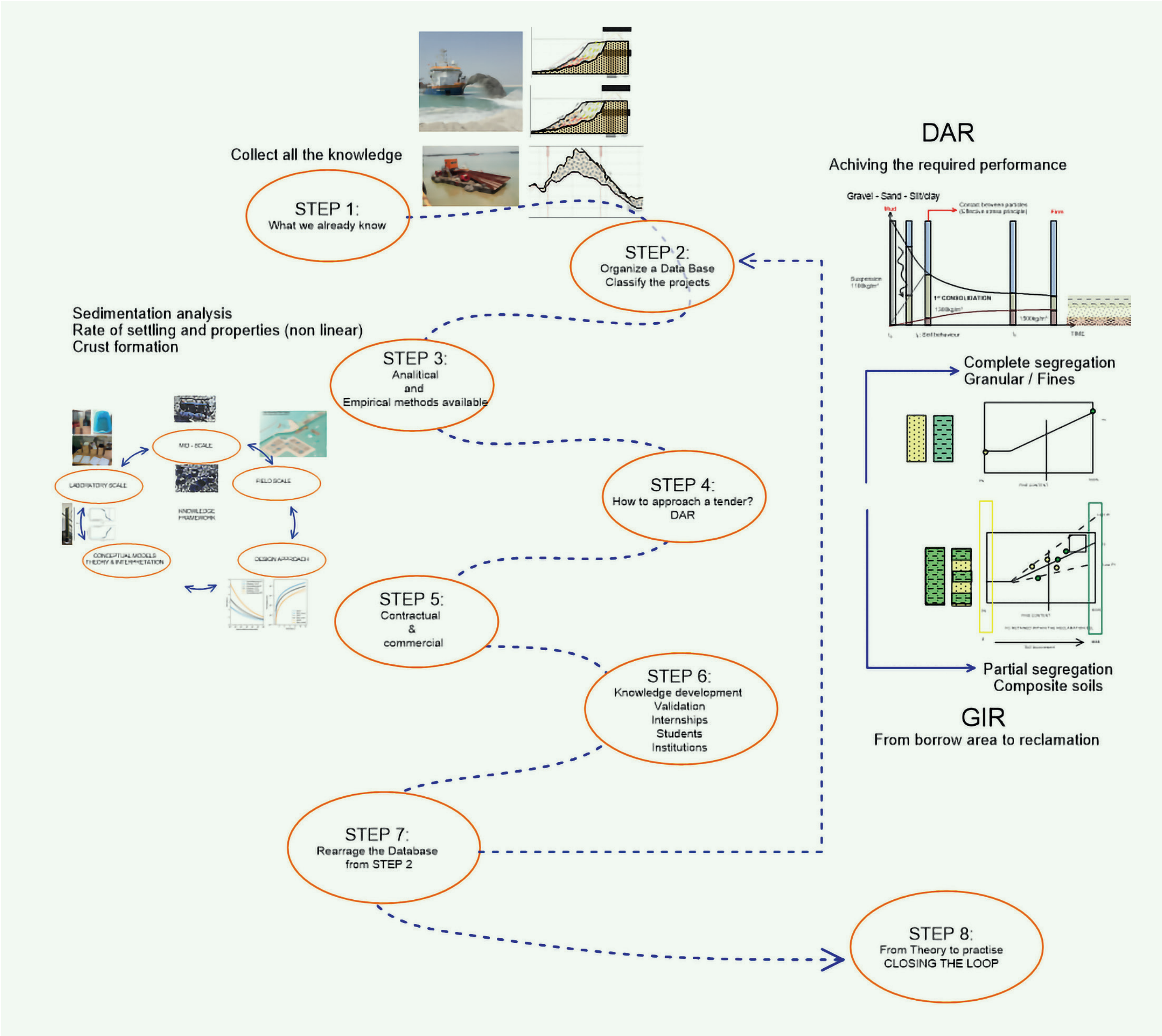

FIGURE 13

Proposed road map.

back to the reclamation project when utilising these materials.

The most efficient dredging work method is project specific and depends on what the client and dredging contractor want to optimise, either the project duration or the project costs. Despite the project specific character of the problem, a model is needed where the production and reclamation processes can interact and the trade-off between cost and duration is assessed for the specific circumstances.

Stakeholders

Stakeholders are recognised to be key players in the implementation of this mindset change and for that their involvement is crucial.

Owners and direct users of the reclaimed land A land reclamation reaches airports, port developments or housing areas. The direct users of a land reclamation are affected by the fact that a land reclamation could enhance their business opportunities. Changes in the project duration will have an impact on the faster or slower return on their investments. Direct users should then be involved in the discussion and their feedback considered for the performance requirements in terms of need for maintenance, costs associated with an increase or decrease in the operability and the overall quality of the end product. The core value regarding this integrated approach is to have a reliable product that does not fail.

Environmentalists and NGOs

The creation of new land by reclamation will potentially affect the current ecosystem, which in principle is not in favour of the environmentalists. The involvement of environmentalists and NGO organisations will favour the realisation of the project and produce a positive effect on the local communities. Introducing solutions like the Building with Nature programme will favour the acceptance of the project by the local communities leading to a better balance between the needs of the project area.

Increasing the efficiency of project execution would result in a shorter relative duration of the construction phase and, as an effect, reduce its negative impact on the ecosystem in terms of noise pollution and disturbance by operations. Choosing the most CO2-neutral dredging work method makes a more healthy and sustainable solution possible. Otherwise, the option for the cheapest work method would allow for some extra budget to build compensation elements on the reclamation, such as new habitats for several species and more value to society (for example, beaches).

The core responsibility of environmentalists and NGOs is to be involved in the discussion to express their opinion on the optimum solution. The core values regarding this integrated framework are trust and transparency regarding the environmental impacts of the execution method of land reclamation and the land reclamation itself.

Contractors

Contractors can increase their project's efficiency in terms of total project costs and duration. This could enable the contractor to increase its competitive position in tenders or increase the profit margin of a project. The contractor will strengthen its market position in the long term. The core responsibility of the contractor is to increase the efficiency of their operations, deliver reliable assets to clients and leave a positive impact on the environment and society. The core values of this civil engineering (CE) system are quality, safety, innovation, and financial responsibility.

Government

The government can benefit from the optimisation of the duration and costs for the completion of a project. Increased efficiency in project execution could lead to cheaper reclamation options, which make the reclamation of land more attractive for various public problems, such as housing, airport expansions and port developments. It is the responsibility of the government to complete a project finding the best solution in terms of sustainability, cost and time. The core values regarding this CE system are safety, sustainability, transparency and public benefit.

Proposed roadmap

In the process of developing an adequate framework for the exchange of knowledge between disciplines and to provide access to this knowledge to all relevant actors involved in these kinds of projects, the following steps are proposed to compose a possible road map (Figure 13).

Step 1: Look into what we already know. A great potential is foreseen from the study of previous cases.
Step 2: Identify solutions for the actual challenges; create and organise a database.
Step 3: Analytical and empirical design methods for reclamation design (segregation and settling velocities) and crust formation are aspects requiring special attention. Developing standard methods for the implementation and interpretation of tests like settling column are of great importance.
Step 4: How to approach a tender process. Client needs contractor's capabilities and stakeholders' interests are to be considered together to achieve the optimal solution.
Step 5: Contractual and commercial aspects. To favour the optimisation of the design and construction of the reclamation, the contractual and commercial aspects should also be elaborated considering a shared risk and benefit from the end result.
Step 6: Research institutions and independent parties are natural places to allocate research projects and knowledge (Figure 14).

Steps 7 and 8: These steps focus on providing the new framework with the corresponding learning elements. Considering the aspects developed in steps 2 to 5, the criteria used for organising the database from previous projects has to be reviewed and the lessons learned properly documented. The proposed road map aims to serve as a starting point for discussion between participants and to identify the needs and views from the relevant actors.

Choosing the most CO2-neutral dredging work method makes a more healthy and sustainable solution possible.

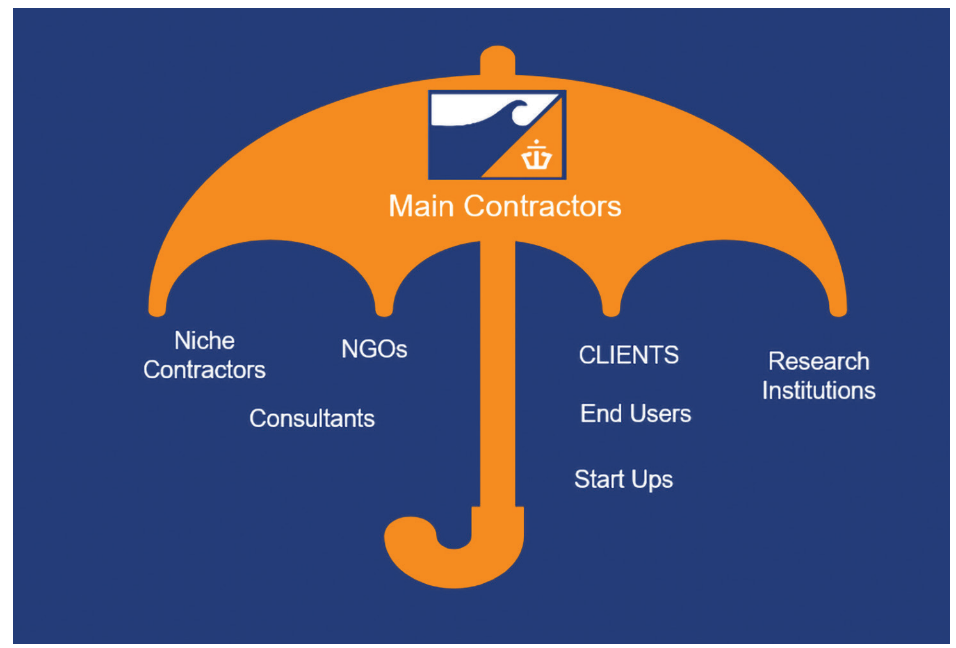

FIGURE 14

Required participants for knowledge validation and framework enablers.

Summary

A paradigm shift is required for the design and construction of reclamation projects, driven by the scarcity of suitable granular materials, environmental limitations, restrictions on sediment spills and the need to achieve a zero-waste balance, i.e. a circular economy. More and more often, the design of reclamation areas is found to be a balance between material availability/reusability and performance requirements.

An adequate conceptual framework is needed to host the trade-off between the production-related aspects and reclamation engineering aspects, and compare them to find a compromise between ideal and possible.

A series of elements and concepts were identified as key players in the development of a new reclamation design paradigm. Engineering aspects such as segregation are considered representative elements bridging the gap of knowledge between production and geotechnical-related aspects.

A possible road map is proposed to shift from the traditional design paradigm to a new one that brings on board all the elements and stakeholders in a proper balance. The departure point for this road map is proposed to be the study of previous cases and the lessons learned from them.

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Clemens is currently completing his MSc degree in civil engineering at Delft University of Technology in the Netherlands. He is a dredging enthusiast with a passion for dredging production and large strain geotechnics. He is currently working on his graduation research at Van Oord on filling the knowledge gap between production and geotechnics in working with soft soils in land reclamations.

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