# The Effect of a Dragging Anchor on a Horizontal Layer of Rockfill

**A Prototype and a Scale Model Test**

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Quantifying the penetration depth of a dragging anchor on a horizontal layer of rockfill provides the possibility to optimize the layer thickness of rockfill layers with a protective function. Current research on this subject is limited and is often aimed at anchor capacities in sand and clay. Penetration behaviour in rockfill is mainly investigated for protections with a limited width.

Anchor dragging tests carried out for a canal expansion project show that as the rock size increases, the penetration depth and the holding capacity of the anchor decrease. A semi-empirical prediction formula is derived.

An additional series of scaled down tests shows that the process of anchor drag in rockfill is scalable, as long as all aspects of the trial design are taken into account. This provides possibilities for accessible further research, expanding on the prediction of penetration depth and further anchor behaviour in different types of rockfill.

## Introduction

In the context of the project "Expansion of the Juliana Canal" in the Netherlands dredging contractor De Vries & van de Wiel (part of the DEME-group) was to design and build a new bed protection. Part of the canal is embedded in gravel type soil layers and lies above ground water level, therefore the canal is covered with a water repellent liner to prevent seepage. For the widening and deepening works, part of this layer needs to be removed and replaced by a new liner.

In the contractor's proposed design, the new water repellent function is provided by a bentonite mat. A filter layer followed by an armour layer, designed to be stable under ship induced currents, is placed on top of this mat. This rock protection should also protect the mat against damage done by dragging anchors (Figure 1).
The available literature on the subject of rockfill cutting was concluded to be insufficient to determine the amount of damage done by anchor drag, required to determine the minimum layer thickness of the new bed protection of the Juliana Canal. Anchor penetration has mainly been investigated in sand and clay in the context of holding capacity and efficient anchor design. Due to the significantly different intrinsic properties of rockfill compared to those of smaller grain sizes, the penetration resistance of the layer will likely vary. Available anchor research in rockfill tends to focus on the protection of pipelines, thus mainly anchors crossing relatively narrow covers. The scenario of anchor dragging over a continuous rockfill layer, is new in that sense.

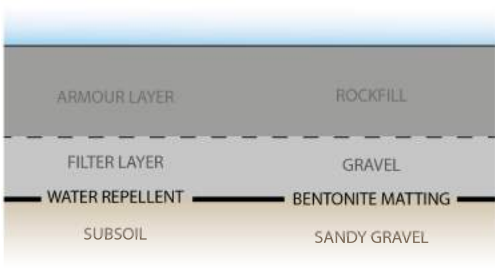


Figure 1: Layer set-up

Crum (2015) presents the results of a series of prototype model tests that were executed to validate the design. Based on these tests, a clear view on anchor behaviour in rockfill is established. A semi-empirical formula is drawn up to predict anchor penetration depth, focussing on the relation between the distance between the fluke distance ($d_{fluke}$: Figure 3) and the size of the rock used in the bottom protection.
Based on the promising results of the study, De Vries & Van de Wiel and the TUDelft decide on additional model testing; comparing the results of the prototype tests for the Juliana Canal with those of a scaled down scenario. The initial aim is to determine the possibility of scaling down an anchor drag test and to determine associated scaling factors. With scaling down proven possible, the following additions to this research can be made:

- Additional rockfill gradings (Varying $D_{50}$) to increase formula range and applicability
- The validity of the formula for different anchor types

With a validated scale model, future testing of anchors in rockfill will become more accessible.

**Objective** The objective of the additional testing program presented in this paper is to design a scale model which accurately represents the penetration process and final penetration depth of a dragging anchor. To verify this model, the tests executed for the Expansion of the Juliana Canal project are used as a reference. By comparing the penetration depth and anchor behaviour of both trials, an evaluation of the representativeness of the scale tests is made.
The main research question is as follows:

*Is the process of anchor drag in rockfill scalable?*

## Anchor Drag Analysis by Crum (2015)

Visual analysis of the tests executed at the Juliana Canal shows that an anchor drag trajectory in rockfill can be split into two phases (Figure 2): The tripping phase and the stationary phase.

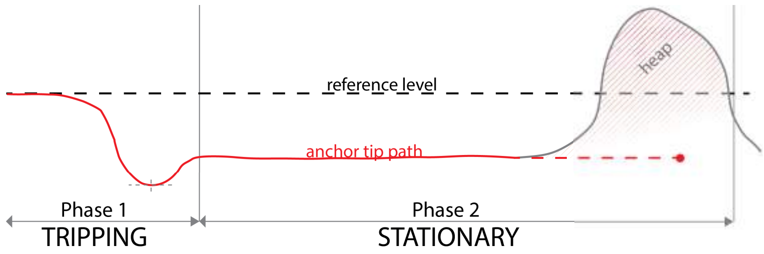


Figure 2: Phase definition in anchor drag in rockfill

The tripping phase is the starting phase where the anchor starts to get dragged and subsequently opens up to dig into the rockfill. Penetration depth increases up till a maximum, while the heap size grows, after which the anchor trips and rises a little. The maximum penetration depth is reached within 2 fluke lengths. Once the anchor has come up and is stabilized, the second phase is reached. During this stationary phase, the penetration depth and heap volume remain constant. The contributing factors to anchor behaviour are summarized by the following observations:

- As the rock size increases, the penetration depth of the anchor decreases.
- As the penetration depth decreases, the anchor holding capacity decreases
- The heap volume(weight) is a determining factor for the anchor holding capacity in rockfill.

There is a clear relation between these three observations as a smaller penetration depth, results in a smaller passive wedge in front of the anchor. Together with the heap volume on top of that wedge, this weight is responsible for a (ultimately smaller) holding capacity of that anchor (Crum, 2015).

The ultimate penetration depth of a one tonne Flipper Delta can be predicted with a semi-empirical formula derived from the results of the prototype trials (Figure 3). This formula contains the parameter $\frac{d_{fluke}}{d_{50}}$, which equals the fluke distance divided by the stone diameter. With this parameter I introduce a physical background into the formula and make it possible to easily translate the formula to different anchor types with similar built. With this design guideline, the ratio between fluke distance and rock size becomes the determining factor in establishing a rockfill layer thickness against anchor penetration.

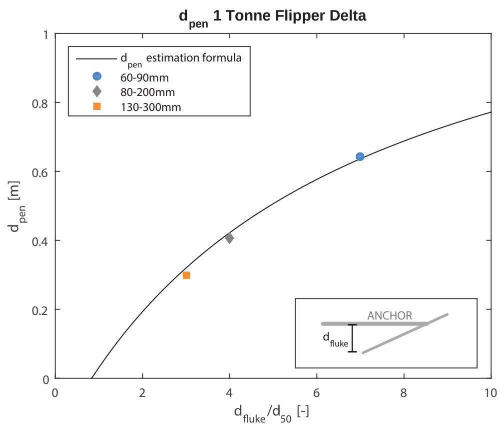


Figure 3: $d_{pen}$ estimation formula

## Test Execution

**Prototype and Scale Set-up**

The prototype tests executed for the Juliana Canal serve as a reference for the scale model tests. Comparing the sizing of Juliana Canal trials to a workable scenario at scale level, resulted in a scale level of $s_L = 7$.
The original tests at the Juliana Canal were executed in a specially built basin, which simulated the design scenario. This basin had dimensions of 25m x 8m x 1m. The layer thickness applied in the basin was 0.55cm (Figure 4). Global Maritime Vryhof made their testing facility available for the additional scale testing of this research. At the testing facility there are several types of scale anchors and a test basin measuring 6.0m x 1.75m at a depth of 1m. The tank is equipped with a winch, which can measure forces at a fixed pulling speed (Figure 5). Three different types of rockfill are tested in the prototype and scaled trials (details in results section):

- PROTOTYPE: 60-90mm SCALE: 9-17mm
- PROTOTYPE: 80-200mm SCALE: 16-25mm
- PROTOTYPE: 130-300mm SCALE: 25-40mm

Anchor dimensions and layer thickness are scaled down linearly as well. The relative density of the anchor and rockfill are equal, only the 80-200mm rockfill has a lower density in the scale test. Both scenarios use a mat to separate the bed layer from the subsoil. As the bentonite matting itself could not be scaled down, ground cover is used in the scale scenario. This textile is woven like the geotextile part of a bentonite mat and could also tear, similarly to what happened in the prototype scenario.
In the case of rockfill, the grains itself and the pores between them are relatively large. Permeability is high; water can flow more easily between areas. Although the effective weight of the stones decreases once submerged in water, during the Juliana Canal prototype testing it became clear that the presence of water does not influence the penetration behaviour of the anchor. For this reason, and because testing is more efficient (faster and with better visibility), water is not used in the scaled set-up.
Anchor speed could not be varied in the testing facility, but was low enough for the anchor to penetrate (0.75m/min). Very high speeds can cause the anchor to bounce over the bed protection. Again, with the absence of water, anchor speed is of less importance because effects like dilatancy cannot occur.


Figure 4: Basin dimensions

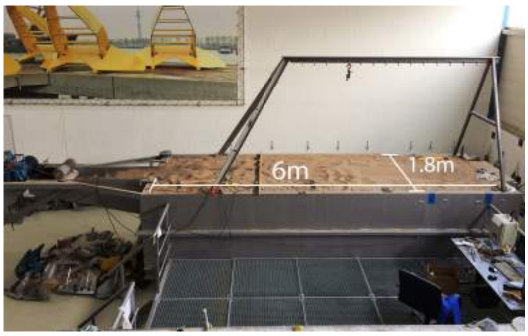


Figure 5: Vryhof testing basin

**Measurement methods** The effect of anchor drag at the Juliana Canal is recorded by tracking points on the anchor and the layer bed with a Trimble GPS measuring tool (Figure 6). The affected surface behind the anchor and the final penetration depth of the anchor were recorded in x,y,z-coordinates in relation to a reference bed level.
Measuring the penetration of the scale anchor was done by using a measurement procedure with two input devices; a total station and a gyro sensor (Figure 7). By attaching a prisma to the anchor, which is followed by the total station, x,y,z coordinates are retrieved. Combining these coordinates with the orientation (pitch, roll or yaw) of the anchor measured by the gyro sensor, a penetration path of the anchor is set out. These measurements are confirmed through frequent manual checks.

Figure 6: Measuring with GPS

Figure 7: Total station set-up

## Results

To compare the scale tests to the prototype, a visual comparison is made of the anchor behaviour, followed by a quantitative check of the penetration depth. The 80-200mm sizing has the largest amount of prototype data and scale data.

### Comparing Anchor Behaviour

To set up a method for comparing anchor behaviour, a standard prototype behaviour is defined. From the Juliana Canal testing it is concluded that the standard behaviour for dragging an anchor through rockfill is the following:

1. The anchor starts to dig in
2. A heap forms in front of the anchor, with rocks rolling from the sides
3. After reaching its maximum penetration depth, the anchor rises slightly until it settles at a constant penetration depth

**60-90mm comparison** [Figure 8 vs. Figure 9]
With the smaller, rounder type of rockfill, a heap forms immediately after start of drag and digging in of the flukes. The overall behaviour of the anchor seems similar to that in the prototype tests. The anchor penetrates until its fluke tips touch the mat (depth: 9cm), where the sound of it scraping over the mat is clearly heard. After eleven tests, the mat is torn, and the anchor penetrates up to a depth of 13cm before the test has to be aborted. This is, when translated, significantly deeper than the penetration depth at the Juliana Canal. In both the prototype and scale scenario we see that the matting gets torn, but the subsoil under the bentonite mat at the Juliana Canal was significantly harder (sand with gravel) than the sand in the scale basin. This might have contributed to smaller final penetration depths at prototype level.

**80-200mm comparison** [Figure 10 vs. Figure 11]
Though penetration depth at a scaled level lies within the expected range, the anchor behaviour is very different. The forming of the heap that occurred at prototype level did not happen during the majority of the scale tests. In the scaled testing the anchor broke out and tilted quickly after starting the pull, never being able to recover. The movement of the anchor through the rockfill is less smooth (more shocks), and the stones do not roll from the heap, whenever a small one was formed.

**130-300mm comparison** [Figure 12 vs. Figure 13]
The anchor behaviour at scale level 130-300 is similar to behaviour at the 80-200 scale tests. The anchor quickly breaks out and has a large amount of roll. After this happens the anchor does not recover. This behaviour is also seen during the prototype tests. However, the roll is less pronounced there. Penetration depth in both tests proved to be minimal.

Figure 8: PROTOTYPE: 60-90mm

Figure 9: SCALE: 60-90mm

Figure 10: PROTOTYPE: 80-200mm

Figure 11: SCALE: 80-200mm

Figure 12: PROTOTYPE: 130-300mm

Figure 13: SCALE: 130-300mm

### Final penetration depth

The averaged final penetration depth together with the maximum and minimum measured value is plotted in Figure 14. Minimum and maximum values are displayed because not all tests consist of sufficient data to be evaluated with a distribution.

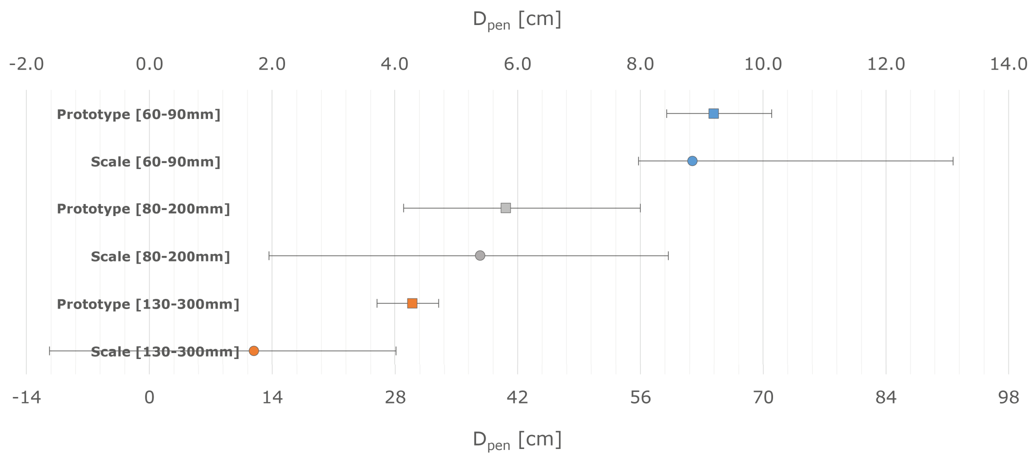


Figure 14: Evaluation of penetration depth

**60-90mm** The penetration depth measured in the scale tests falls within the range of measurements at prototype level except for the maximum penetration depth. This might be explained, as mentioned earlier, by the different soil type under the layer. The layer starts at the same depth for both tests, but a softer subsoil in the scale tests will give larger maximum results, once the layer is torn.

**80-200mm** It can be seen from Figure 14 that the penetration depths of the 80-200mm comparison tests closely match each other with only a 10% smaller scaled penetration depth. However, one must keep in mind that the anchor did behave differently in both scenarios.

**130-300mm** The penetration depth in the larger rockfill, though not exactly comparable in amount of penetration, does still show the same overall trend in relation to the other results; larger rockfill corresponds with larger penetration. In this type of rockfill, only four scale tests were executed, so it is difficult to make solid conclusions on the exact penetration depth. Especially, since some of the results of the scale test show no penetration at all. If non-penetrating trials are to be excluded, the scaled results would match the prototype results more closely.

**Overall evaluation** Overall, penetration depths of scaled tests correspond well to the expected values. The same trend, where larger rockfill results in smaller penetration, remains present in both scenarios.

The range of results is larger at scale level, which is expected, because of the greater margin of error in measuring equipment at such small scale. Also, at scale level, outliers tend to be more extreme. Figure 15 shows that all results measured at prototype level fit within the $\mu \pm 2\sigma$ range (95% occurency) of the scale tests when normally distributed.

This could mean that after executing a fair amount of scale runs, enough data is obtained to minimize risks at prototype level.

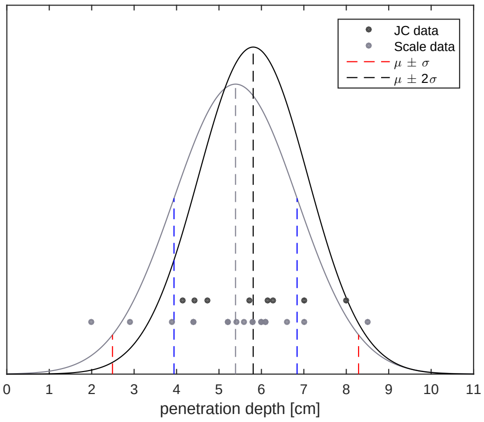


Figure 15: Normal distribution of results

## Comparing Rockfill

Different behaviour in the scale tests can be explained by different properties of the rockfill.The main properties that affect penetration depth are found to be:

1. Rock sizing ($D_{50}$)
2. Angularity

**Sizing** The relative sizings (in sieve-distributions) are shown in Figure 16.

- The sizing of the 60-90mm rockfill matches closely, mainly in the mid-range. This explains the matching anchor behaviour.
- The scaled 80-200mm rockfill is smaller than used in the prototype tests. This does not explain that the anchor penetrates with more difficulty, under the assumption that the larger the rock is, the less the anchor will penetrate.
- The 130-300mm rockfill in the scale tests is larger than used in the prototype tests. This can explain the smaller penetration depth.

In the Appendix, a visual comparison of the all the different rockfill used is made in Table 1.

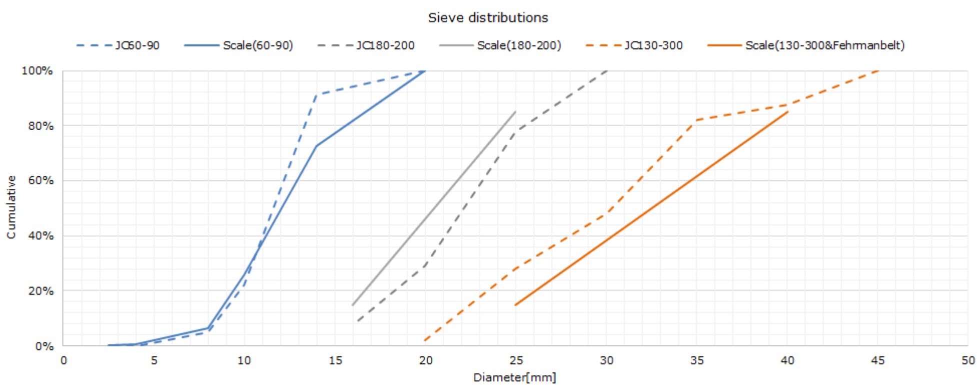


Figure 16: Relative sieve distributions

**Angularity** The Juliana Canal rockfill used is classified as river gravel. Therefore, though it is not round, it does have more rounded edges due to erosion. The rocks used at the scale tests for the 80-200 and 130-300mm are a lot more angular and have a larger proportion of broken surfaces.
It is possible, that as a result of the higher angularity in the scaled rockfill, the cohesion of the whole rockfill pack is higher, due to stronger rock-columns. The layer is then more difficult to penetrate as the individual rocks in the layer are packed tighter and are more fixed in their position. This can explain that the anchor tilts quickly after penetration and no heap is formed. Because the more angular rockfill does not roll over each other, the build-up of such a heap becomes more difficult.
A visual representation of the difference in angularity of the tested rockfill is given in Figure 17 ("S" for scale tests, "P" for prototype).

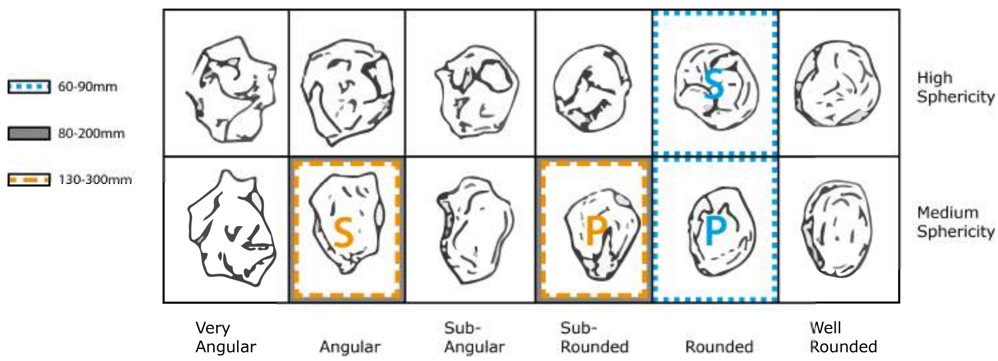


Figure 17: Comparison of angularity

## Re-assessment of the Estimation Formula

The semi empirical formula is set up to estimate anchor drag penetration in rockfill by Crum (2015), using the data obtained from the Juliana Canal trials. This formula is based on the assumption of two bounding conditions depending on the relation between the fluke distance and the rock size; bot a minimum penetration and a maximum possible penetration. The minimum penetration depth of an anchor is considered zero penetration. The hypothesis is that this occurs around $d_{fluke}/d_{50} < 0.5$, where a rock is twice the size of the fluke distance. Penetration depth will increase as the rock size decreases. Sand, when looking at the shape and structure of an individual grain, can be considered the smallest rock size possible. The theoretical penetration in sand is reported to be 1 fluke length (Flipper Delta, API (1996)). Both of these boundaries are closely met in the estimation formula based solely on the results at the Juliana Canal.

When adding the scaled data and test results from different anchor types, the vertical axis is made dimensionless by dividing by the fluke distance of the respective anchor size and type. In all tests the $d_{fluke}/d_{50}$ is rounded, referring to only whole numbers of stone.
Several tests with a StevinMk3 anchor using its clay angle (50°) and sand angle (32°)

are executed in the scaled 130-300mm rockfill. All results are plotted in Figure 19. A StevinMk3 anchor, though shaped a little differently, is a high holding capacity anchor with an adjustable wedge, like the Flipper Delta.
It can be concluded that a larger fluke distance does not guarantee more penetration in rockfill, as the results with a 50° angle and therefore a relatively large fluke distance, show a penetration depth close to zero (Figure 14). As stated by The Anchor Manual (2010) the penetration of an anchor into certain soil type is greatly influenced by the selected fluke angle. In hard soil, if an anchor is set to a 50° angle the anchor will fail to penetrate into the seabed and will begin to trip, fall aside and slide along the seabed. This behaviour is now confirmed for anchors in rockfill specifically.
The tests with the StevinMk3 anchor and the sand angle (32°) give results in the vicinity of the penetration depth prediction formula. More tests with this anchor type and different rockfill are necessary to fully conclude if the exact same formula can be used, or a adjustment for different anchor types is necessary.

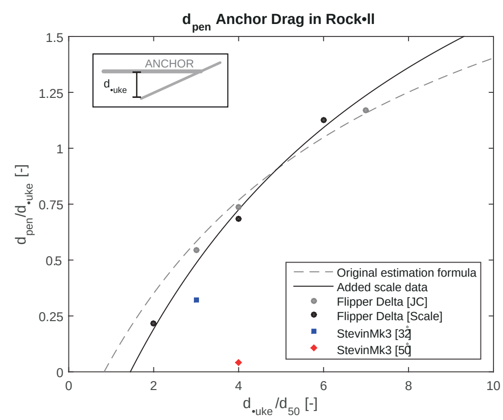


Figure 18: Fitting with the new scale data

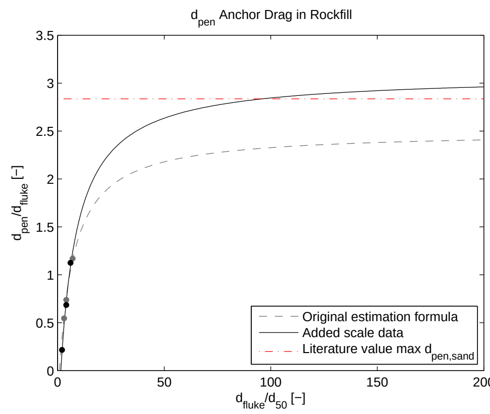


Figure 19: Penetration limits

A new fit, through both the prototype and the scaled Flipper Delta data gives an estimation for $d_{pen} = 0$ at $d_{fluke}/d_{50} < 1.5$. It can be reasoned that the limit for penetration lies at 0.5, as stated earlier. It is also possible that the turning point of penetration or no penetration lies at a higher $d_{fluke}/d_{50}$. More tests around this area of $0.5 < d_{fluke}/d_{50} < 4$ can confirm this critical point of zero penetration.
The literature value for maximum penetration lies at 1 fluke length ($L_{fluke,1tonneFD} = 1.56m$), translating to $d_{pen}/d_{fluke} = 1.56/0.55 = 2.8$ (Figure 19) for a Flipper Delta anchor. Both the old and the new estimation of the formula give maximum boundaries close to this value.

Still, the data set is small. If more data with different rock sizes is added, further affirmation of this formula could be given. A larger data set on a different anchor, as the StevinMk3 can confirm if the same formula is to be used, or if the slightly different shape of the anchor results in a translation factor or a totally different behaviour.

# Conclusion

Test observations in a scale basin confirmed, what also was concluded from the prototype tests at the Juliana Canal: a larger (smaller) grain diameter correlates with a

smaller (larger) anchor penetration depth and a more limited (higher) anchor holding capacity. Both the prototype and scaled trials show an anchor path that digs in initially and then rises to find an equilibrium depth. The forming of the heap is clearly present at those tests with the more rounded rockfill. The scaled tests of the 80-200 and 130-300mm both make use of a slightly more angular rockfill than the prototype stones. This might explain the less distinct forming of the heap and heavier tripping and rolling of the anchor.
With respect to penetration depth, the scale tests give results in the same order of magnitude as gained from the prototype trials. Averages of the scale tests lie within a 10% range of the depths recorded at the Juliana Canal tests. Scale tests do give a greater range of results which can be accredited to the higher chance of occurrence of measurement errors and possibly to the larger relative step-size in the rockfill grading. Given also the same trend for varying rockfill sizes and the matching anchor behaviour at the smallest and largest rock types, it can be concluded that the process of anchor drag is scalable in an layer of rockfill. It is not necessary to scale the water, if the main interest of research is anchor penetration depth. When testing at scale level, it is likely that up-scaled results will give a safe estimation of the penetration range. Extra attention should always be paid to the reconstruction of the full set of circumstances, which all have effect on the penetration behaviour. It should be noted that besides scaling down the anchor size and rockfill, one should especially acknowledge:

- Maintaining the same level of angularity whilst scaling
- Ensuring the scaled reconstruction of the sublayer(s)

Adding the scale tests results in a new estimation within the physical boundaries set upon the semi-empirical formula. The estimation is optimized to a smaller penetration in the lower $d_{fluke}/d_{50}$ range. Maximum penetration depth is still estimated at 1 fluke length by the formula based on the extended data set.

**Recommendations** More trials can add to the certainty of the estimation formula. Investigating in especially the lower $d_{fluke}/d_{50}$ range ($2 < d_{fluke}/d_{50} < 6$) will optimize the design guideline for rockfill bed protection. Extra data on the effect of the angularity of rockfill is also desirable.
It is recommended to test both again with the Flipper Delta and StevinMk3 amongst other anchor types with similar build into equal rockfill layers. More results are needed to conclude if the same estimation formula can be used for each anchor type, or the formula should be adjusted. Differently shaped anchor types with fluke angles $> 50°$ are projected not to penetrate into rockfill, but confirmation by trials is advised. The knowledge gathered from these trials can be used to optimize layer thickness in designs that have protection covers against dragging anchors.
As it is now known that anchors do not penetrate deeply into rockfill layers and the holding capacity is reduced significantly, it is advised to convey this information to skippers who are sailing at areas with rockfill bottom cover. Preventing anchorage in these vulnerable areas can avert scenarios in which unnecessary extra damage occurs.
The use of the design formula together with a confirmation via (scale) model testing can be an efficient way to optimize designs of for example, river bottom protection on water repellent layers, under water tunnel protection armour layers and scour protection in area's with anchoring risk.

## References

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## Appendix

Table 1: Visual comparison of rock size

| 60-90mm | 80-200mm | 130-300mm |
|---|---|---|
|  |  |  |
| 9-17mm | 16-25mm | 25-40mm |
|  |  |  |