CHAPTER VII
LESSONS FROM TAILINGS FACILITY DATA DISCLOSURES

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1. INTRODUCTION AND SUMMARY OF FINDINGS

In this chapter we report on lessons derived from an analysis of the most comprehensive global survey of tailings facilities ever undertaken. The data are derived from information disclosures by publicly listed companies, following a request by the Church of England Pensions Board and the Council on Ethics of the Swedish National Pension Funds. The request was made on behalf of the Investor Mining and Tailings Safety Initiative, a group of 112 investors that represent US$14 trillion in assets under management. The information disclosures reveal new data on 1743 unique tailings facilities, containing 44.54 billion m^3 of waste material.[1]

The chapter analyses this unique dataset for the first time, presenting findings across a range of topics, including facility construction method, consequence of failure, the number of facilities that have reported at least one past stability issue, volume of tailings under storage, and the rate of uptake of alternative technologies to dewater tailings and reduce geotechnical risk. While the findings presented here are only the beginning of the potential insights that can be generated from the current dataset, they represent a significant advancement of the science on tailings facilities.

Although the dataset does not capture all tailings facilities (see Box 1), it does represent 30 per cent of contemporary global commodity production, with 83 per cent of the market capitalisation of publicly listed companies in the industry responding to the disclosure request. This significant representation of active facilities makes it possible to scale trends within the data to generate global estimates for some parameters.

Our analysis finds that the number of tailings facilities has significantly increased over time. The number of facilities doubled between 1955 and 1969 (14 years), doubled again between 1969 and 1989 (20 years) and again between 1989 and 2020 (31 years). We project the total number of active tailings facilities worldwide to be around 3,250 and the total number of active, inactive and closed facilities around 8,500. This estimate is calculated by scaling the number of facilities reported in the dataset to global mineral production as reported by the United States Geological Survey mineral commodity summaries.

Box 1: Data limitations

There may be incentives for companies to under-report on parameters such as the existence of past stability issues, and to that extent the analysis and data presented herein should be considered conservative. The failure of tailings facilities also has the effect of contributing to under-reporting by the very fact that in some cases those facilities no longer exist and thus their characteristics are not disclosed.

The method used to request information disclosure on tailings facilities from publicly-listed contemporary companies has produced a dataset that is likely more representative of active tailings facilities, omitting some closed facilities and the large number of abandoned facilities for which there is no longer an owner responsible. There is also a possibility that the survey under-samples less diligent companies, with lower governance standards, who failed to respond to the disclosure request.

The dataset does not include information from companies that are not publicly listed, such as state-owned entities, privately-owned companies, and many mid-sized and junior companies, contributing to an under-representation of facilities in countries such as China and Chile, and potentially an over-representation of larger facilities.

Planned generation of tailings over the coming five years is 2.5 billion m^3 per year for the reporting companies, with the total planned tailings under storage expected to be 56.2 billion m^3, which represents a 26 per cent increase in tailings under storage over this five-year period. When scaled to global mineral production we estimate 11.1 billion m^3 of additional tailings is expected to require storage in tailings facilities per year over the coming five-year period (14.4 billion *t*). Baker *et al.* (this volume) used mineral production and ore grades for a wide range of commodities to estimate an annual output of 8.85 billion *t* of tailings for 2016.

Of the reported tailings facilities, the upstream construction method is the most common, followed by downstream construction. Centreline, hybrid,[2] and single raise construction methods are the next most common. In-pit/natural landform and dry-stacked are the least common construction methods. While upstream facilities currently make up 37 per cent of total reported number of facilities, they have declined from a peak of 85 per cent of facilities constructed in 1920-1929 to 19 per cent of new facilities in 2010-2019. However, there is variation across commodities.

Analysis of the incidence of past stability issues reveals strong trends across tailings facility raise types and other parameters.[3] Upstream and hybrid facilities are the most likely to have reported a past stability issue when normalised against the frequency of each raise type, with 18 per cent of active upstream facilities reporting ‘notable stability concerns’ or failure to be ‘confirmed or certified as stable’ at some point in their history. The normalised prevalence of past stability issues reported by active upstream facilities is twice that of downstream facilities and six times as many as dry-stack facilities. No active in-pit/natural landform facilities reported a past stability issue. These observations are consistent with analyses of tailings facility failures, which show a greater prevalence of failure for upstream facilities than for other raise types (ICOLD and UNEP 2001).[4]

Taller and larger facilities (by volume) are also more likely to have reported a past stability issue, although facilities over 100m in height show fewer issues, perhaps due to higher standards of construction. The relationship with seismic hazard is complex. As seismic hazard increases, facilities are initially less likely to have reported a stability issue, which may be explained by the lower proportion of upstream and hybrid facilities in this fraction or the possibility that facilities are built to higher standards of construction in earthquake prone regions. However, at locations of high and very high seismic hazard, the likelihood of a facility reporting a past stability issue increases.

Hybrid, upstream, downstream and centreline tailings facilities were found to be associated with a significantly higher consequence of facility failure than those for dry-stack, single raise and in-pit/natural landform facilities, as determined by company-

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[1] For a sense of scale, if this volume were spread evenly across an area the size of Manhattan island, it would be higher than all the skyscrapers.

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[2] The term ‘hybrid’ facility is used here to refer to facilities where multiple raise methods are utilised in the same facility over time.

[3] We refer to stability issues throughout the chapter as synonymous with *geotechnical* stability, acknowledging that the *geochemical* stability of tailings is a critically important issue, but not one addressed by the disclosures.

[4] In their analysis of tailings facility failures ICOLD and UNEP (2001:20) find a greater prevalence of failures for upstream facilities, though they qualify this by stating: ‘The [*stability*] incidents must be reviewed in terms of the number of particular dam types in operation. The upstream method is the oldest and most commonly used method of tailings dam construction.’ Elsewhere, ICOLD and UNEP (2001:24) argue that ‘In general, dams built by the downstream or centreline method are much safer than those built by the upstream method, particularly when subject to earthquake shaking.’

commissioned modelling during facility design and construction.[5] Given that upstream facilities have been considered by ICOLD and UNEP (2001) as less safe than downstream and centreline facilities, it could be expected that the construction of these facilities is avoided in locations where the potential consequence of failure is high, however, this does not appear to be the case.

The removal of water from tailings to generate thickened, paste or filtered tailings is an important innovation in tailings practice that has been identified by a significant number of authors as having the potential to improve geotechnical and geochemical stability (Nguyen and Boger 1998; Boger 2009; Boger *et al.* 2006; Jewell and Fourie 2006; Davies *et al.* 2011; Franks *et al.* 2011; Edraki *et al.* 2014). Tailings dewatering has been identified as a priority by individual mining companies and peak industry bodies (see for example, ICMM 2019). Analysis of the disclosures shows that the uptake of filtered and in-situ dewatering of tailings has not significantly increased over recent decades.

The findings reported here complement those from analyses of individual tailings facility failures, such as those reported by Morgenstern *et al.* (2015; 2016) and Robertson *et al.* (2019), and the analysis of datasets of multiple tailings facility failures, such as those reported by ICOLD and UNEP (2001), Azam and Li (2010), and Bowker and Chambers (2017).

2. BACKGROUND AND METHODS

On April 5, 2019, the Church of England (CoE) Pensions Board and the Council on Ethics of the Swedish National Pension Funds, on behalf of 112 investors, representing US$14 trillion in assets under management, wrote to Board Chairs and Chief Executive Officers of listed extractive companies and requested specific disclosure on tailings facilities (CoE and Swedish Council on Ethics, 2019a). The disclosure questions were developed in consultation with independent technical advisors, the ICMM Secretariat and four mining companies. Barrie *et al.* (this volume) provide a full list of the disclosure questions. The letter requested that the responses be uploaded to the company website, signed by the CEO or Board Chair. A follow-up letter was sent on April 17, setting an extended deadline of June 7, 2019 for the disclosure (CoE and Swedish Council on Ethics, 2019b). Correspondence was sent to a total of 727 companies, representing publicly listed mining, as well as oil and gas companies. The later were included due to the potential exposure to tailings from oil sands operations and joint ventures.

A specialist Environmental, Social and Governance (ESG) financial services provider was commissioned to compile the list of companies and distribute the letter requesting disclosure. The list of companies was generated using the Global Industry Classification Standard.[6] An additional 88 small and mid-market companies not listed in the above codes were added by investor participants in the initiative.

The request specified that companies should report all tailings facilities where the company has any interest, through subsidiaries, partnerships, joint ventures both incorporated and unincorporated, and any other enterprises of whatever legal form. All joint venture partners were requested to report on jointly owned facilities, even if the reporting company was not the operating partner.

Of the 727 companies contacted:

- 339 responded (representing 47 per cent of the companies contacted)
- 187 of these companies confirmed they did not have tailings facilities (representing 55 per cent of those responding and 26 per cent of all companies)
- 152 confirmed they did have tailings facilities.

As of March 2020, 45 of the companies that confirmed exposure to tailings facilities had not published their disclosure on a website or asked for extra time to complete their disclosure.

For the mining sector specifically:

- 45 out of the 50 largest mining companies by market capitalisation in the world responded
- 83 per cent of the industry by market capitalisation responded
- 60 per cent of the industry by market capitalisation publicly disclosed
- All 23 out of 23 publicly listed members of the International Council on Mining and Metals (ICMM) publicly disclosed.

The proportion of market capitalisation of the respondents was calculated on 4 November 2019 using the Thomson Reuters Eikon financial data platform.

In December of 2019 and January of 2020, a compilation of the disclosed data was sent to each reporting company for verification. The majority of disclosing companies responded to this extra request, resulting in 86 per cent of the entries of the dataset being subject to this additional layer of verification. A full list of the companies that were contacted and the status of their disclosure is publicly available and published on the Investor Mining and Tailings Safety Initiative website (CoE and Swedish Council on Ethics, 2019c). The version of the dataset analysed in this chapter was current as at February 26, 2020.

Due to duplicate reporting by multiple owners, the disclosures were corrected for analysis to represent only unique tailings facilities. Where there were discrepancies in the reported data by multiple owners of the same facility, we prioritised data for analysis which were disclosed by the operating companies. Where the ownership of the facility was a separate joint-venture company, we prioritised the data reported by the owner with the highest ownership share. In the case of 50/50 joint ventures, we prioritised the data of the owner by alphabetical order.

Each 'tailings facility' in the dataset represents a unique tailings structure. In some cases, tailings facilities may consist of multiple structures. This generated a second type of duplicate in the raw data that is relevant for calculations of volume. Companies that reported facilities with multiple structures sometimes reported the same total volume and planned volume for multiple data entries. In our calculations of volume, duplicate data have been corrected by evenly distributing the reported volume against the number of structures that make up the facility. It is also worth noting that 'tailings facilities' in the dataset include tailings production at mines, but also tailings, slimes, ash and other wastes produced at mineral processing and smelting facilities.

With funding support from the United Nations Environment Program (UNEP) and the Investor Mining and Tailings Safety Initiative, GRID-Arendal compiled the data into a database for analysis. The individual company disclosures were compiled independently by two additional research teams from The University of Queensland and The University of the Witwatersrand, and shared with the GRID-Arendal team for cross-checking, comparison and data-cleaning. A searchable online database of the disclosures was published by GRID-Arendal on the 24th of January 2020, as the Global Tailings Portal (http://tailing.grida.no).

The S&P Global Metals and Mining Industry database was used to assign individual mine site mineral production to the active tailings facility entries. The most recent S&P Global production figures (2018) were used.[7] All tailings production was assigned to the primary commodity of the operation. Global mineral production figures from the United States Geological Survey (USGS), *Mineral Commodity Summaries* (2019, reporting 2018 data) were used to calculate the representativeness of the dataset as a function of global production and to project a global estimate of tailings production and number of facilities.[8] The tailings facility dataset represents an average of 30.2 per cent of global commodity production. The relatively high sample rate provides confidence in the global representativeness of the dataset for active tailings facilities.

The tailings production (as stored in tailings facilities) for each mine was calculated by using the annual average of the planned tailings storage in five-years, which was reported by the companies. Production data is available in the S&P database for a range of commodities (bauxite, coal, cobalt, copper, diamonds, gold, iron ore, lanthanides, lead, lithium, molybdenum, nickel, niobium, palladium, phosphate, platinum, potash, silver, tin, uranium, zinc). For commodities where production data is not available from the S&P Global database or cannot be matched with USGS production data (alumina, aluminium, borates, chromite, ferrochrome, ferromanganese, ferrovanadium, ilmenite, manganese, rutile, tantalum, titanium, vanadium, oil sands, refineries, smelters, power plants), which represents 16 per cent of the reported active facilities, the average coverage of the other commodities (30.2%) was used to project the global estimate. The number of tailings facilities was estimated by projecting the proportion of global production represented by the mines in the tailings

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[5] A tailings dam breach analysis is conducted by a dam safety professional to identify and characterise threats to public safety and the environment. The results are typically presented as inundation and deposition maps and used to classify the consequence of a potential failure of a facility, as well as to assist in emergency planning, dam safety management, failure mitigation planning, and mine closure and dam decommissioning planning (Martin et al. 2019).

[6] Companies in the following sub-industry codes were contacted: oil and gas drilling, oil and gas exploration and production, integrated oil and gas, coal and consumable fuels, fertilizers and agricultural chemicals, aluminium, diversified metals and mining, copper, gold, precious metals and minerals, silver, steel, and construction materials.

[7] Except bauxite, where the most recent production data available in the S&P Global database was 2016.

[8] USGS commodity summaries do not include artisanal and small-scale mining production, for which extraction is commonly of placer deposits with consequent low production of tails.

facility dataset for active mines. If a constant sample rate is assumed between active, inactive and closed facilities then an estimate can also be calculated for the total number of facilities.

Data on seismic hazard were derived from the Global Seismic Hazard Assessment Program (Zhang *et al.* 1999) which provides a global dataset of seismic risk based on Peak Ground Acceleration risk estimates. Data on wind was sourced from Global Wind Atlas (2017), and data on precipitation sourced from Fick and Hijmans (2017).

3. FINDINGS

3.1 TAILINGS PRODUCTION

A total of 44.54 billion m^3 of tailings is currently under storage by the facilities disclosed in the dataset. Expected generation of tailings over the coming five years is 2.52 billion m^3 per year for the reporting companies (2019-2023), with a 26 per cent increase in tailings under storage over this five-year period to 56.2 billion m^3 at January 2024. When these numbers are scaled to represent global mineral production we estimate 11.1 billion m^3 (14.4 billion *t*)[9] of additional tailings will require storage per year over the coming five-year period.[10] This annual estimate of worldwide increase in tailings requiring storage (see Figure 1) is higher than the global tailings production estimates reported by Baker *et al.* (this volume), who used mineral production and ore grades to estimate 8.85 billion *t* of tailings produced per year in 2016 for a range of commodities.

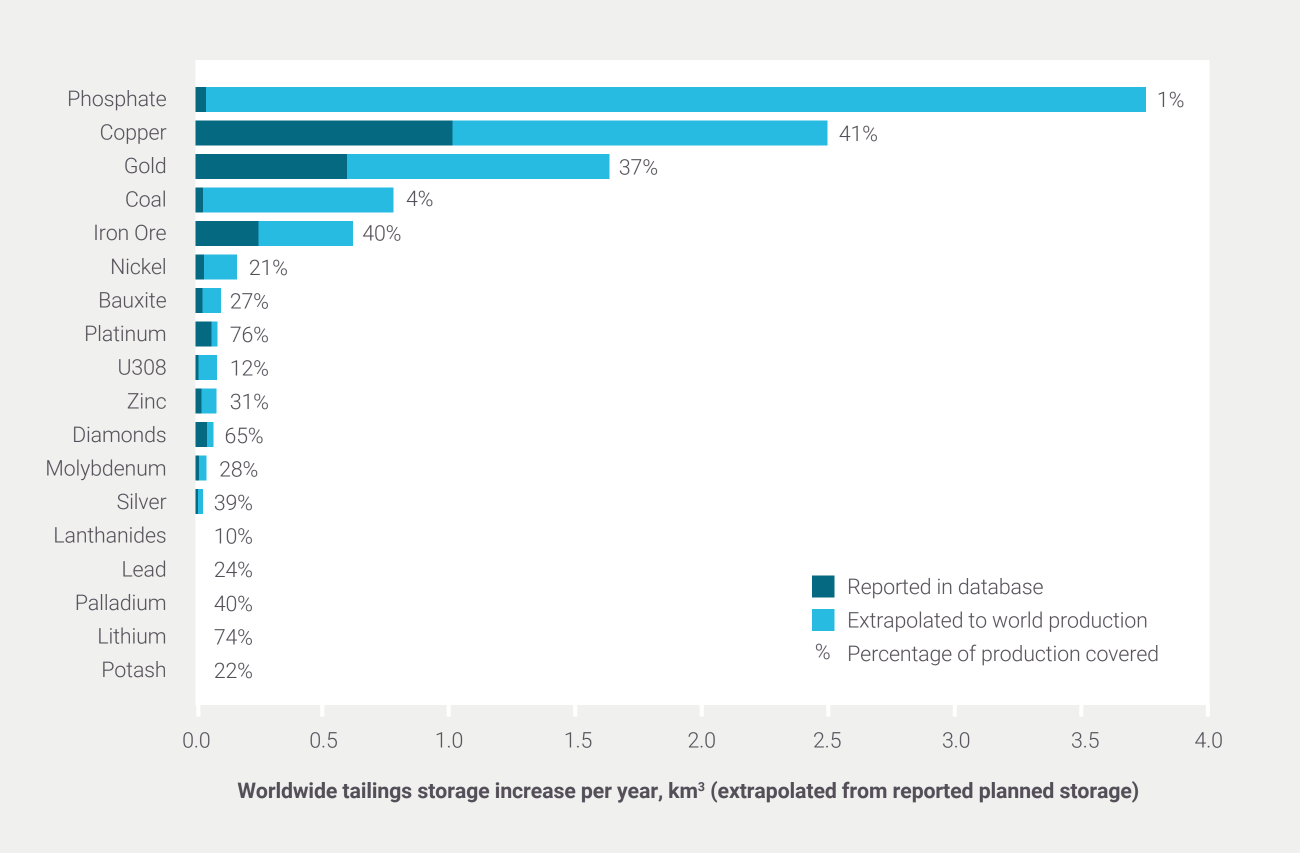

Figure 1. Tailings storage increase per year for a range of commodities as reported in the dataset and extrapolated to world production

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[9] Tailings production by weight calculated assuming the modal average of tailings bulk density reported by 20 companies as part of the disclosures (1.3 t/m^3). The reprocessing and reclamation of tailings (a type of negative production of tailings) was not considered in the calculation of expected future tailings production.

[10] This estimate does not include tailings that are not stored in a tailings facility (e.g. tailings backfill and heap leach pads).

3.2 NUMBER OF FACILITIES AND THEIR MANAGEMENT

A total of 1743 unique facilities are reported in the dataset (725 of which are currently active). This number has significantly increased over time as illustrated by Figure 2, which shows the number of tailings facilities by decade of construction.

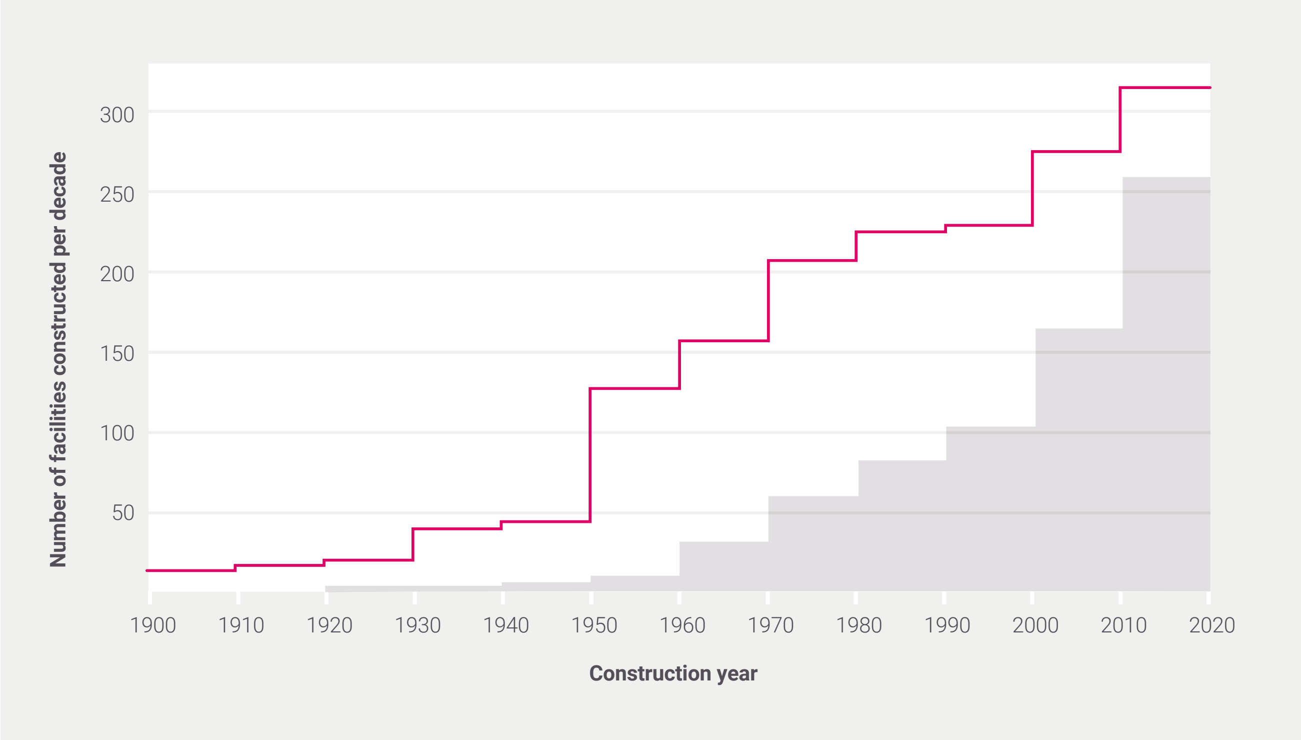

Figure 2. Tailings facilities by decade of construction

Note: shading indicates active facilities

The number of tailings facilities doubled between 1955 and 1969 (14 years), doubled again between 1969 and 1989 (20 years) and again between 1989 and 2020 (31 years). The largest reported facility by tailings under storage is 1.56 billion m^3. The largest active tailings storage facility by volume of tailings under storage is 1.19 billion m^3. The mean facility volume for all facilities is 26.3 million m^3 and for active-facilities-only is 43.7 million m^3, which may indicate an increase in individual facility volume over time.

We estimate that the total number of active tailings facilities worldwide is around 3,250 and the total number of active, inactive and closed facilities is 8,500. This estimate was calculated using the reported number of facilities projected to global commodity production using USGS mineral commodity production estimates. Due to the data considerations outlined in Box 1 it is important to note that this is a conservative estimate that does not include abandoned facilities. Davies and Martin (2000) cite a global estimate of 3,500 tailings facilities, while Yin *et al.* (2011) cite 12,000 facilities just in China. Other researchers have estimated as many as 18,000 facilities (Brown and Elliott 2019). However, the methods for determining the aforementioned estimates are unknown, and it is not clear whether they refer to active, inactive, closed, or abandoned facilities.

Companies reported that most facilities keep full and complete engineering records (85 per cent), have an accompanying closure plan (93 per cent), and include long-term monitoring in their closure plans (87 per cent). Oversight of the management of the facilities is predominantly undertaken jointly by both external engineering specialists and in-house professionals (72 per cent), followed by external-only (20 per cent) and internal-only oversight (6 per cent). For around two per cent of the facilities (46 in total) it was not clear whether they were under any kind of engineering oversight. Three of these facilities reported a past stability issue.

3.3 CONSTRUCTION METHODS

Figure 3 shows the total number of tailings facilities in the database, categorised by raise type. The upstream construction method is historically the most common, followed by downstream construction. Centreline, hybrid, and single raise construction methods are the next most common. In-pit/natural landform and dry-stacked are the least common facility types.[11]

While upstream facilities make up 37 per cent of total reported facilities, they have declined from a peak of 85 per cent of new facilities in 1920-1929 to 19 per cent of new facilities in 2010-2019 (see Figure 4). Upstream facilities make-up 43 per cent of facilities that are inactive, closed or reclaimed. In the past twenty years the number of new downstream and in-pit/natural landform facilities have risen sharply, while the number of new upstream facilities has declined.

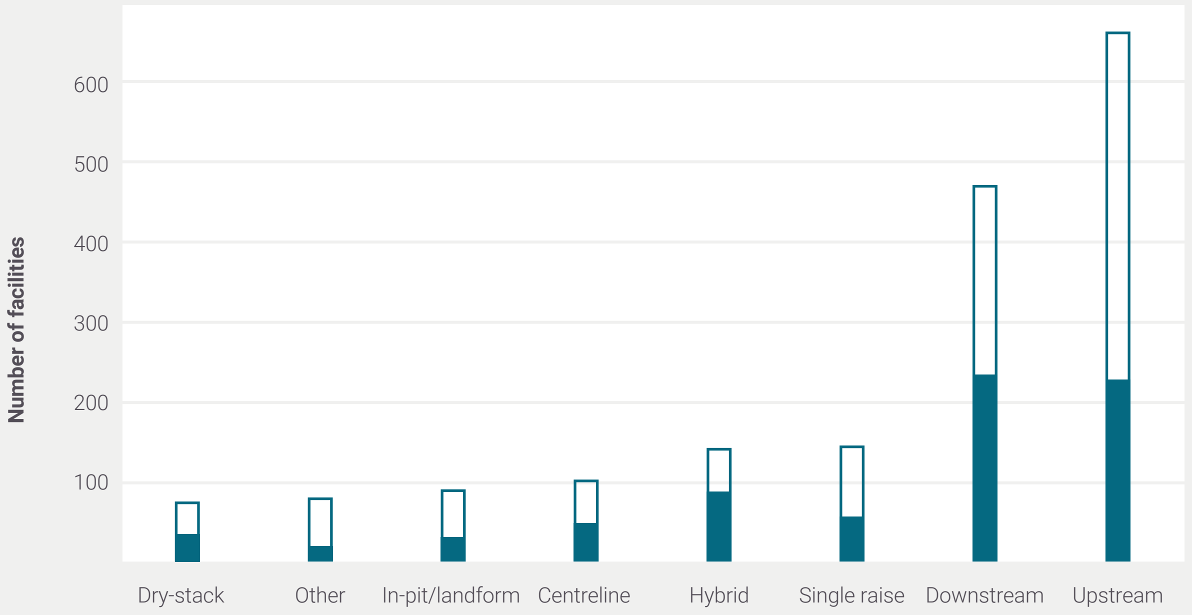

Figure 3. Tailings facilities by raise type

Note: shading indicates active facilities

The relative frequency of facility construction methods varies by continent, which is due to a range of factors, including commodity, ore type, climate, seismic hazard, topography, and governance (see Figure 5). Upstream facilities now represent a relatively low number of active facilities in North and South America when compared to Africa and Oceania. This may partly reflect different regulatory approaches; for example, upstream facilities were banned in Chile following the La Ligua earthquake in 1965 and the collapse of the El Cobre tailings facilities, which resulted in the deaths of more than 200 people.

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[11] For data analysis purposes Modified Centreline facilities were categorized together with Centreline facilities. Operations that produce paste or thickened tailings were classified by companies by the facility raise type, rather than whether the tailings themselves have been dewatered. A small number of Central Thickened Discharge facilities were reported in the dataset, but not enough to undertake meaningful analysis.

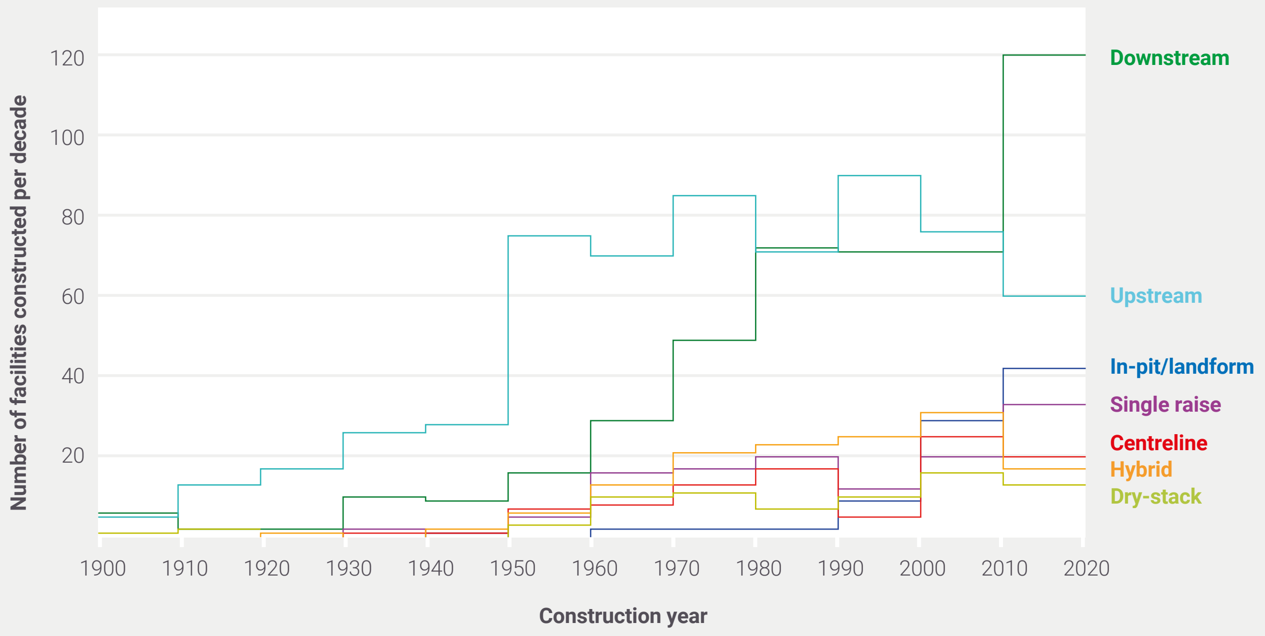

Figure 4. Number of facilities constructed per decade by raise type

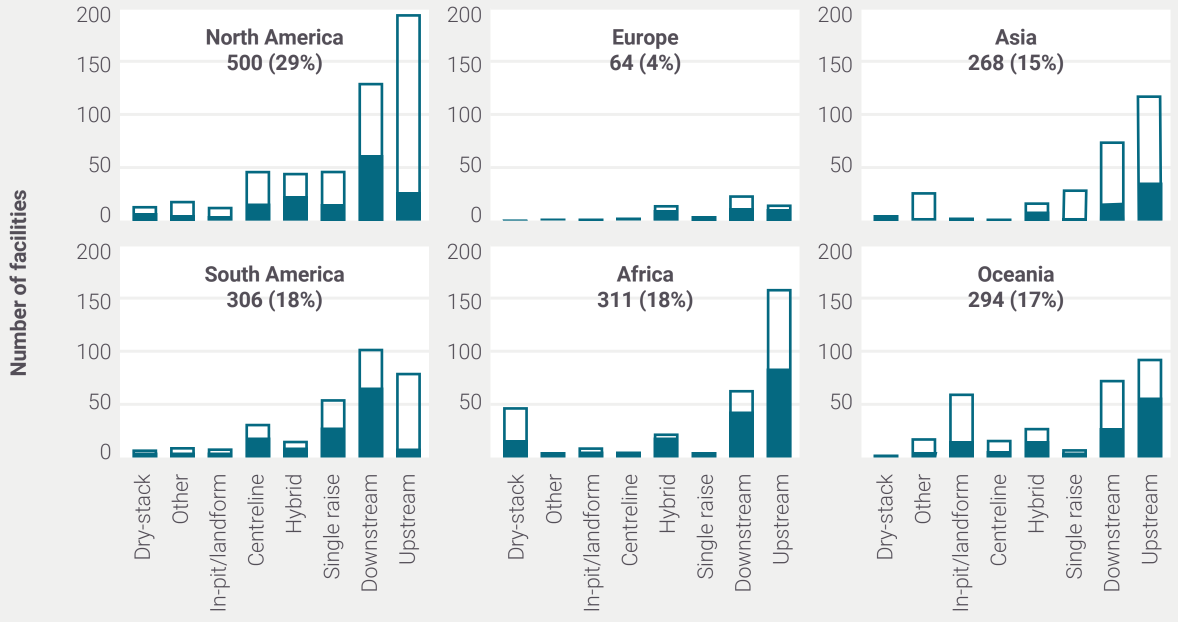

Figure 5. Distribution of tailings facility raise type by continent[12]

Note: shading indicates active facilities

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[12] Countries are assigned to continents according to https://www.geonames.org/countries/.

The volume of tailings under storage also varies with facility construction methods. Upstream facilities contain the highest total volume of tailings under storage, followed by downstream, hybrid and centreline, single raise, in-pit/natural landform, dry-stack and other facilities (see Figure 6). The highest median volume of tailings stored per facility are hybrid facilities (18.3 million m^3), followed by centreline (7.3 million m^3) and upstream (5.9 million m^3).

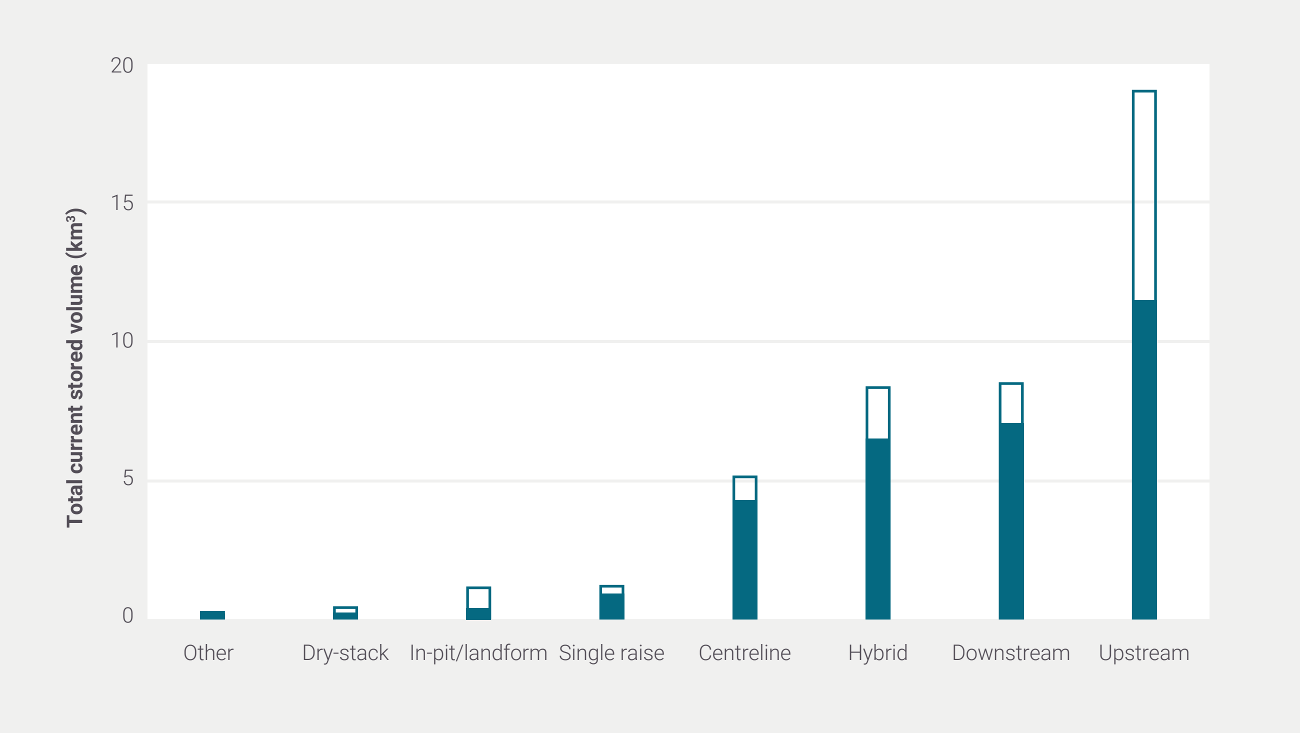

Figure 6. Current volume of tailings under storage (in cubic kilometres) by raise type of active, inactive and closed facilities

Note: shading indicates active facilities

3.4 INCIDENCE OF PAST STABILITY ISSUES

Companies were requested to disclose any situation where a facility, 'at any point in its history, failed to be confirmed or certified as stable, or experienced notable stability concerns, as identified by an independent engineer (even if later certified as stable by the same or a different firm).' The reported issues ranged in seriousness from relatively minor to major issues. In total 10 per cent of facilities reported having experienced a past stability issue. The data exhibits distinct trends according to construction method, governance, age, height, volume and seismic hazard.

Upstream and hybrid facilities were the most likely to report a past stability issue, when normalised against the frequency of each raise type. They were followed by centreline, downstream and single raise facilities (see Figure 7). The likelihood of a past stability issue having been reported by active upstream facilities is twice that of active downstream facilities and six times as many as active dry-stack facilities. No active in-pit/natural landform facilities reported a past stability issue. From a geotechnical perspective the rate of past stability issues is significant (> 1 per cent) for most construction methods, highlighting the universal importance of careful facility management and governance.[13]

One limitation of the dataset is that the occurrence of multiple instances of past stability issues at the same facility is not recorded. This may have the effect of undercounting the prevalence of stability issues for facilities prone to experiencing them. Due to this limitation, the findings are not a calculation of the rate of instability over a normalised period of time; however, they do enable the comparison of general stability trends between facility types.

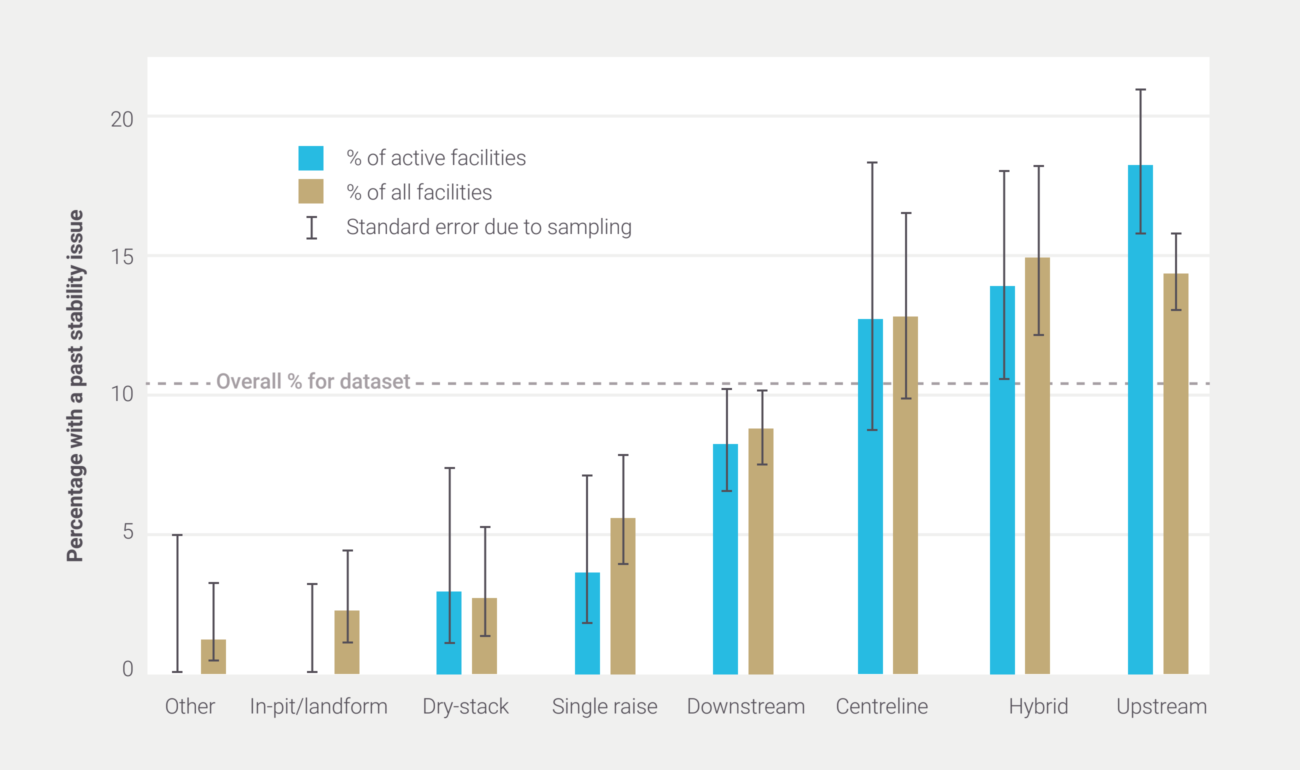

Figure 7. Proportion of facilities with a past stability issue by raise type[14]

It is possible that the incidence of past stability issues for any one particular construction method is not a function of the unique characteristics of these facilities, but rather, an artefact of the distribution of that facility type across other common characteristics known to influence geotechnical stability. For example, a particular construction method might have a greater proportion of facilities that are older, higher, larger, located in lower governance settings, in regions with a greater seismic hazard, or where rainfall is higher. These differentially distributed attributes might lead to these facilities demonstrating a higher or lower incidence of past stability issues, for reasons unrelated to the construction method. In the remainder of this section we will explore the influence of these factors on the past stability of the tailings facilities. At the conclusion of this section we return to the question of whether the higher prevalence of past stability issues reported by upstream facilities is an artefact of the distribution of these facilities or a feature of the construction method itself.

Tailings facilities located in OECD-countries, as well as those operated by ICMM-member companies generally reported a lower normalised incidence of past stability issue across those raise types that were elevated (see Table 1). This finding lends some weight to the view that tailings governance plays some role in ensuring geotechnical stability. However, the proportion of facilities reporting past stability issues for facilities located in OECD-countries and those operated by ICMM-member companies, remains high in absolute terms across a number of raise types (most notably upstream, hybrid and centreline).

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[13] Construction practices that have been reported to improve geotechnical performance of conventional tailings facilities include: comprehensive characterisation of both the tailings and underlying soils, keeping the size of the decant pool as small as possible, allowing the development of long beaches to promote the desiccation and densification of tailings, and continuous monitoring of the disposal facilities (Williams, this volume; Santamarina et al. 2019).

[14] Error bar lengths here, and in subsequent figures, are binomial confidence intervals for the subsample represented by each bar, showing +/-1 standard error (approximately 68%).

Table 1. Occurrence of a past stability issue by raise type and governance context

Raise Type	All facilities	Active-only facilities	OECD countries (active-only)	Non-OECD countries (active-only)	ICMM member (active-only)	Non-ICMM member (active-only)
Upstream	94 of 653 (14.4%)	41 of 224 (18.3%)	12 of 87 (13.8%)	29 of 137 (21.2%)	24 of 142 (16.9%)	17 of 82 (20.7%)
Downstream	41 of 464 (8.8%)	19 of 230 (8.3%)	7 of 106 (6.6%)	12 of 124 (9.7%)	8 of 128 (6.2%)	11 of 102 (10.8%)
Hybrid	21 of 140 (15.0%)	12 of 86 (14.0%)	7 of 46 (15.2%)	5 of 40 (12.5%)	4 of 34 (11.8%)	8 of 52 (15.4%)
Centreline	13 of 101 (12.9%)	6 of 47 (12.8%)	2 of 25 (8.0%)	4 of 22 (18.2%)	3 of 31 (9.7%)	3 of 16 (18.8%)
Single raise	8 of 143 (5.6%)	2 of 55 (3.6%)	2 of 22 (9.1%)	0 of 33 (0.0%)	0 of 40 (0.0%)	2 of 15 (13.3%)
In-pit/ landform	2 of 89 (2.2%)	0 of 30 (0.0%)	0 of 20 (0.0%)	0 of 10 (0.0%)	0 of 17 (0.0%)	0 of 13 (0.0%)
Dry-stack	2 of 74 (2.7%)	1 of 34 (2.9%)	0 of 10 (0.0%)	1 of 24 (4.2%)	1 of 25 (4.0%)	0 of 9 (0.0%)
Other	1 of 79 (1.3%)	0 of 19 (0.0%)	0 of 12 (0.0%)	0 of 7 (0.0%)	0 of 12 (0.0%)	0 of 7 (0.0%)

All other things being equal, we would expect older structures to be more likely to have reported a stability issue than younger structures. This is because older facilities have had a longer opportunity for a stability issue to manifest. To control for this, we mapped the number of facilities that had reported a past stability issue against the age of the facility in years. This was done for all active facilities, and for all active upstream, downstream and dry-stack facilities specifically. The results are presented in Figure 8, which shows the number of facilities reporting a past stability issue, by facility age and the proportion of facilities of different ages that had reported a stability issue.

As to be expected, a higher proportion of long-active conventional tailings facilities reported a past stability issue. Upstream facilities demonstrate a relatively higher prevalence of stability issues just ten to twenty years after construction. The very small number of active dry-stack facilities reporting a past stability issue (1) produces an artefact of apparently high proportion of stability concerns at facilities aged 40-50 years old, due to this being the age of the single active dry-stack facility with a past stability issue.

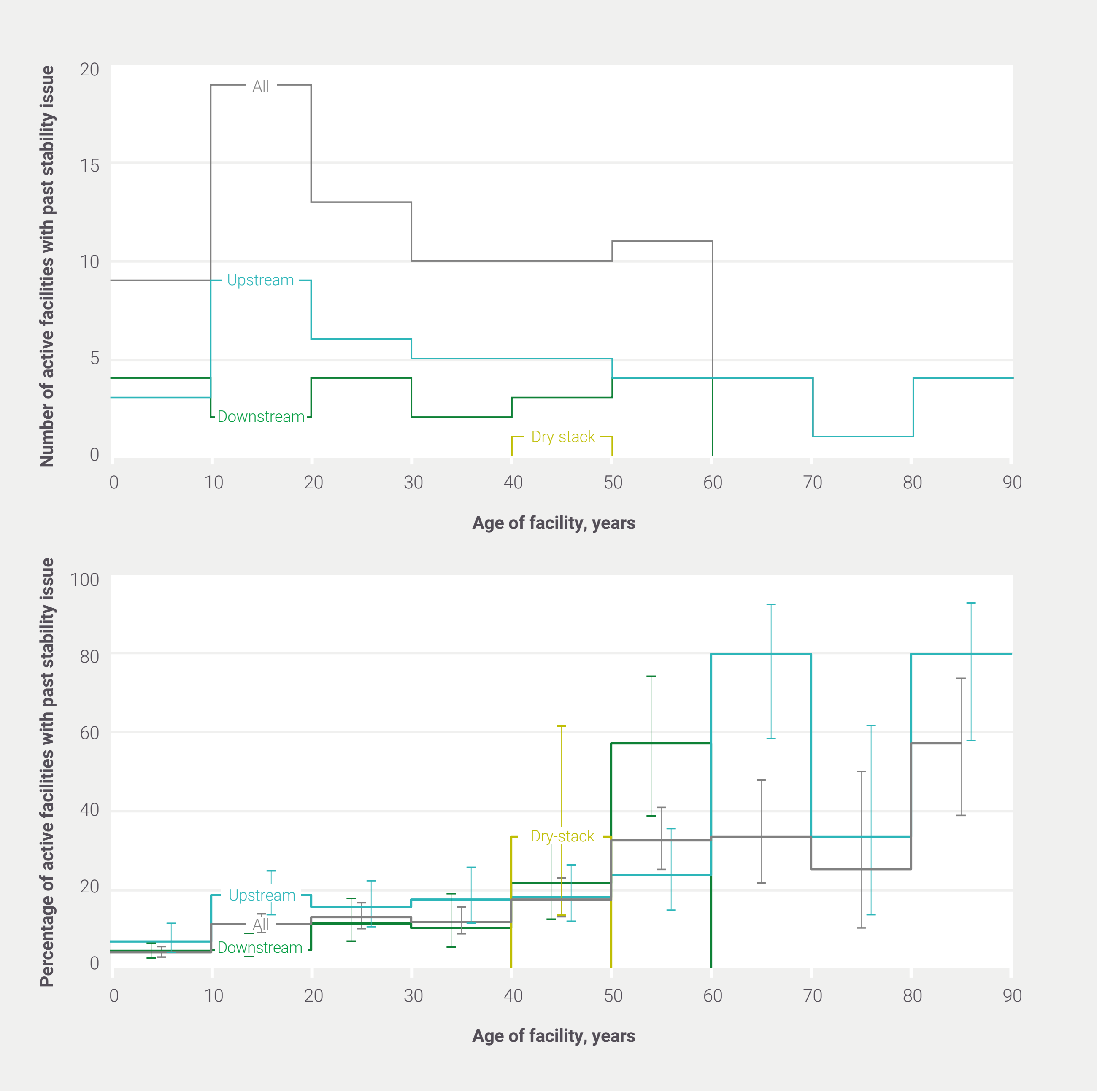

Figure 8. Relationship between facility age, facility raise type and past stability issue

Note: Top graphic shows number of active facilities reporting a past stability issue; bottom graphic shows proportion of active facilities in each age category reporting a past stability issue

The dataset also points to a relationship between facility embankment height and whether a facility had reported a past stability issue, but this relationship is not straightforward (see Figure 9). The likelihood of a past stability issue being reported for a facility with an embankment between 80-100m is notably 5 times higher than for facilities with embankments between 0-20m. But in the relatively small number of cases where an embankment height exceeds 100m, there is a decline in the proportion of facilities that reported a past stability issue. A possible explanation for this, may be that higher standards of construction have been applied for facilities with very high embankments (although we have no direct measure of this).

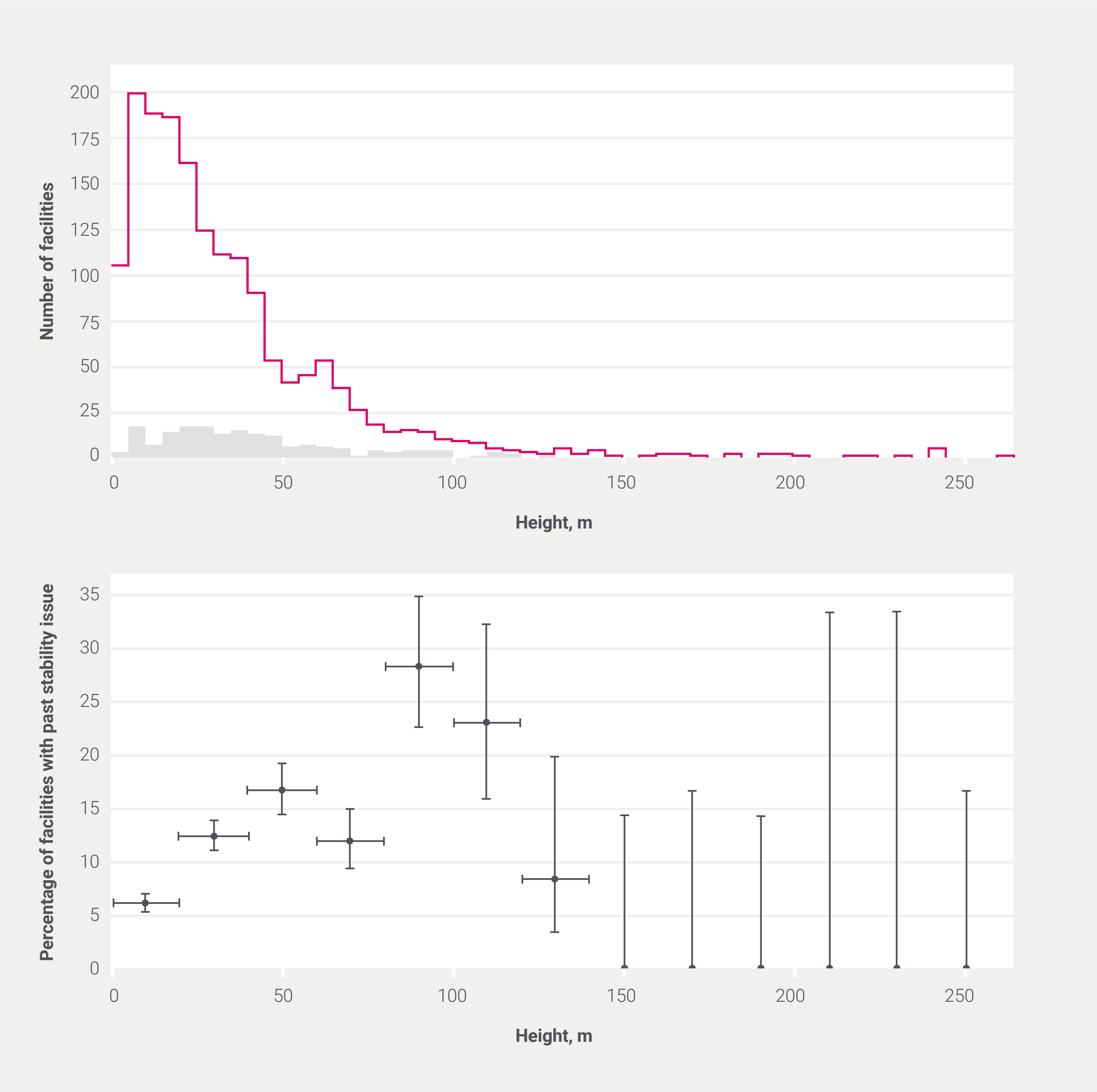

Figure 9. Relationship between facility embankment height and reported occurrence of past stability issues, all facilities[15]

Note 1: Top graphic shows distribution of tailings facilities by embankment height; shading indicates number of facilities reporting a past stability issue.
Note 2: Bottom graphic shows proportion of facilities reporting a past stability issue by embankment height.

We also found that the larger the facility, the more likely it is to have reported a past stability issue (see Figure 10). Due to the very large range of reported volumes, from just 10m^3 to over 1 billion m^3, a logarithmic scale is used to display the distribution. The broad trend in stability issues this reveals should be interpreted accordingly: similar *proportional* increases in volume (e.g. 10 times greater) seem to be associated with similar *absolute* increases in the fraction with issues (e.g. 5% higher). This analysis cannot distinguish between the possibility that the increased incidence is due to the greater surface area of the material, the greater stress from the increased mass, or the potential for these or other factors (such as age) to act in combination.

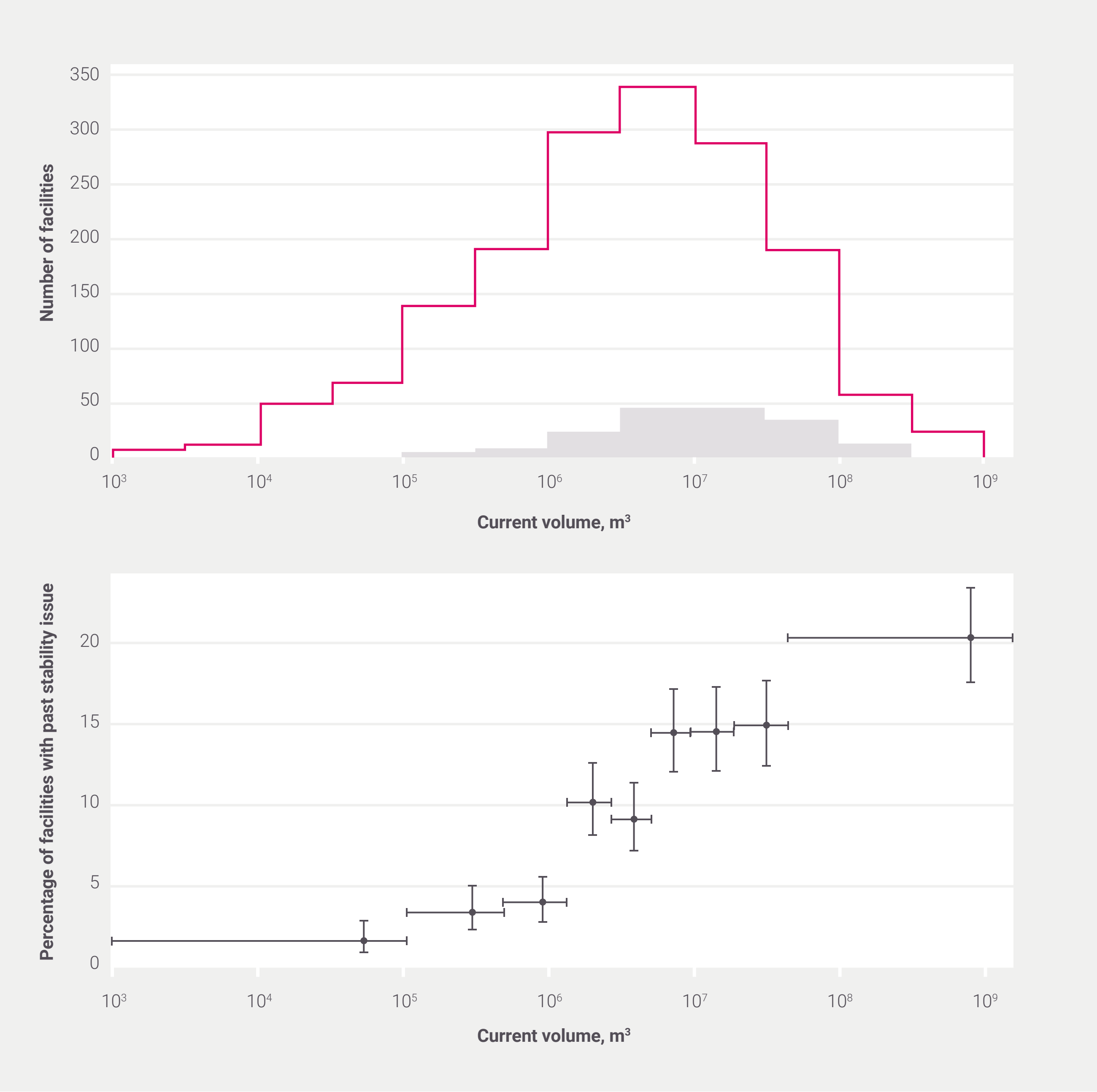

Figure 10. Relationship between facility volume and history of past stability issue, all facilities

Note 1: Shading in top graphic indicates number of facilities reporting a past stability issue
Note 2: Top graphic shows distribution of tailings facilities by volume; bottom graphic shows proportion of facilities reporting a past stability issue by facility volume.

Seismicity is another factor that may affect the stability of a facility. Facilities built in seismically active regions might be expected to show a higher incidence of past stability issues. Figure 11 shows the distribution of tailings facilities by seismic hazard and the proportion of tailings facilities with a past stability issue by seismic hazard.

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[15] There are no instances of stability issues in heights above 140m. Vertical error bars for these categories show the range of fractions for which the probability of finding zero in a sample of that size is greater than 74% (the same confidence interval as shown for the other points).

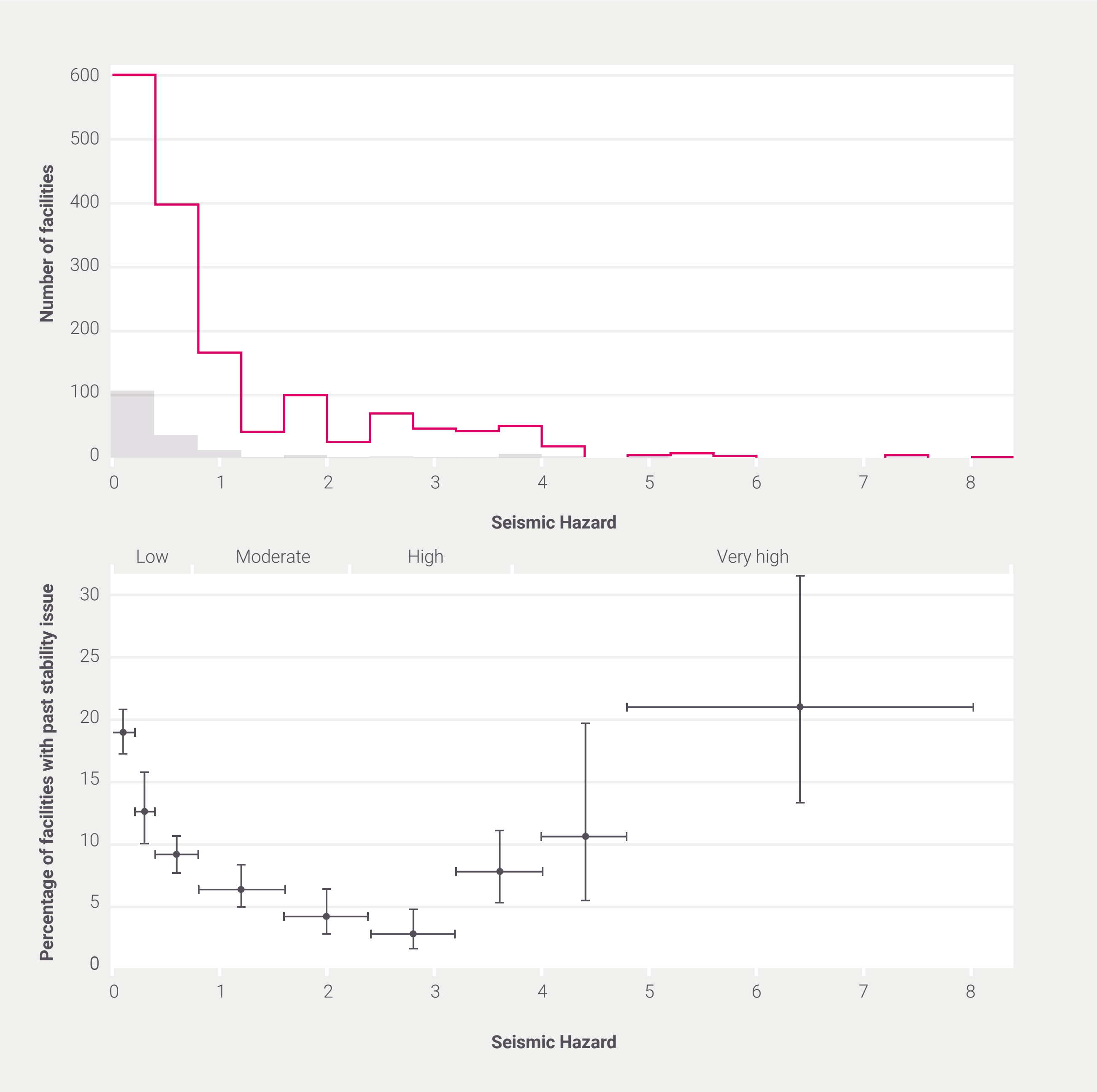

Figure 11. Relationship between seismic hazard and history of past stability issue, all facilities

Note 1: Top graphic shows distribution of tailings facilities by seismic hazard; shading indicates number of facilities reporting a past stability issue.
Note 2: Bottom graphic shows proportion of past stability issue by seismic hazard as defined by the Global Seismic Hazard Assessment programme

Most facilities are built in locations with a seismic hazard below 1. As seismic hazard increases, the likelihood of a facility having reported a stability issue initially decreases. However, above a seismic hazard of three, the proportion of facilities reporting a past stability issue then increases. This relationship is not attributable to other factors that may be changing coincidentally with seismic hazard. In particular, facility height and storage volume do not change significantly for any given range in seismic hazard.

It is worth noting that the proportion of upstream facilities is lower in seismically active regions, with a corresponding increase in downstream facilities

(see Figure 12). This may be due to concerns by governments and companies about the relative stability of the upstream raise type and may be a factor in the lower likelihood of reported stability issue with increasing seismic hazard (between 0-3). Another possible interpretation for the described trend (though one for which we do not have direct data), is that facilities in locations with elevated seismic hazard may be built to higher standards of construction than facilities in locations with very low seismic hazard, thus leading to an initial improvement in geotechnical stability with increasing seismic hazard. However, above a certain point of seismic hazard (3+), facility stability may be reduced even for those facilities built to higher construction standards.

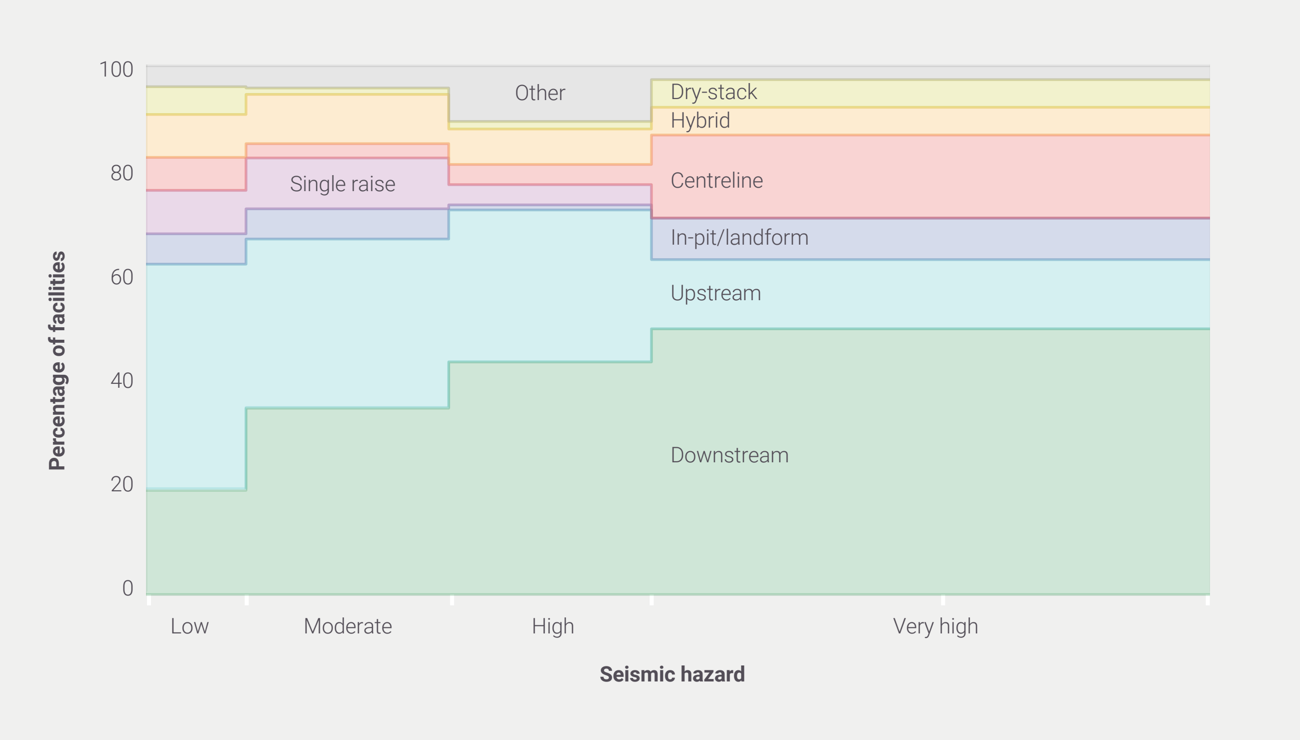

Figure 12. Proportion of facility raise type by seismic hazard

We now return to the question of how to account for the higher proportion of upstream facilities that report a past stability issue. Could this be just an artefact of the other properties that these facilities happen to have (age, dimensions, seismic hazard etc.), and not a feature of the construction method itself?

The result in Figure 7 showed that the relative frequency of stability issues in the upstream subsample is a few standard errors above that for the dataset as a whole. If these subsamples of different raise types were no different in any other respect (i.e. unbiased), this would be a high-confidence result, but they are not. For example, the distribution in facility age for the subsamples is not the same. As this section has now shown, the distribution of stability issues also varies by facility size, height and location. This raises the possibility that these could be the real underlying reasons for the difference in the past stability issues seen in Figure 7. This is a hypothesis that can be tested. If it were true, and we took any two subsamples from the dataset which had almost identical distributions in these variables, we would expect to find almost the same stability fraction in both subsamples; even if one sample is comprised entirely of facilities with a given raise type, and the other contains none.

To carry out this test, we generated two such subsamples. The first contains all the upstream facilities that have known values for all parameters (559 facilities). To generate the second, we take all facilities with other raise types that have known parameter values (864), and select a test subsample that matches the size and distribution of the upstream subsample. To make the test robust, 100 different versions of the test subsample were generated by randomly selecting within constraints to match the distributions. The distributions of these, and of the upstream sample, are shown in Figure 13.

In the upstream subsample, 82 (14.7%) of facilities have had past stability issues. In the test samples, the average number was under 59 (10.5%), slightly higher than the overall non-upstream stability fraction (8.8%). If the two samples had the same underlying likelihood of stability issues, as in our hypothesis, the probability of them differing by this much (23 or more) would be very low – about 3 per cent. This margin is sufficient that any further corrections for the remaining differences in the parameter distributions would be unlikely to reverse the result of the test. The result provides a high confidence confirmation (greater than 95%) that the observed higher likelihood of stability issues in upstream facilities is not an artefact of these other properties.

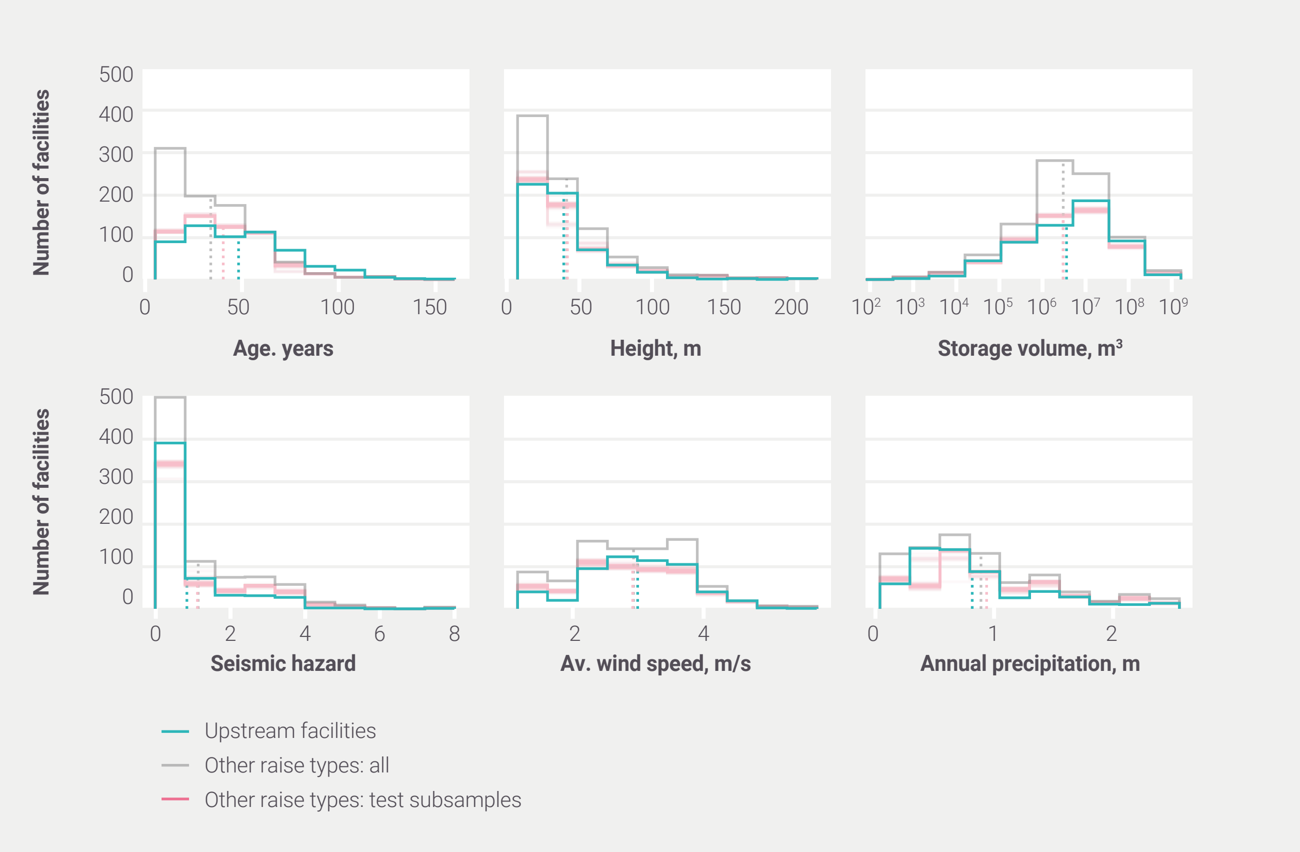

Figure 13. Distribution of the two subsamples of facilities across six quantitative variables that may be related to stability issues

Note 1: The vertical dotted lines show the mean of each subsample. (In the case of the test subsamples, this shows the mean of all 100 versions.)
Note 2: The underlying distribution of the variables in the other raise types is also shown for comparison.

3.5 CONSEQUENCES OF FAILURE

The consequence category for each tailings facility was reported by the companies. Consequence ratings are typically classified as part of modelling undertaken in the facility design and construction phase. The categories correspond to various country-level, industry and corporate classification systems, using different metrics of consequence. Tailings facilities were classified against a total of 62 different classification schemes. The five most common schemes reported in the dataset are listed in Table 2. Collectively these schemes cover 68 per cent of all facilities and 76 per cent of currently active facilities.

Table 2. Five most common consequence classification schemes reported against in the dataset[16]

Name	Number (all facilities)	Number (active facilities)
Canadian Dam Association (CDA)	577 (33.1%)	225 (31.0%)
Australian National Committee on Large Dams (ANCOLD)	243 (13.9%)	128 (17.7%)
South African National Standards (SANS)	158 (9.1%)	87 (12.0%)
Brazilian Ordinance 70.389/17 (BRA)	114 (6.5%)	63 (8.7%)
Anglo American Technical Standard (AA)	98 (5.6%)	47 (6.5%)
Total	1190 of 1743 (68.3%)	550 of 725 (75.9%)

Figure 14 shows the frequency of the distribution of active facilities by consequence category for each of the five most common schemes[17]. For the AA, SANS and BRA schemes, a trend is apparent where a greater number of facilities are classified by progressively higher consequence of failure ratings.

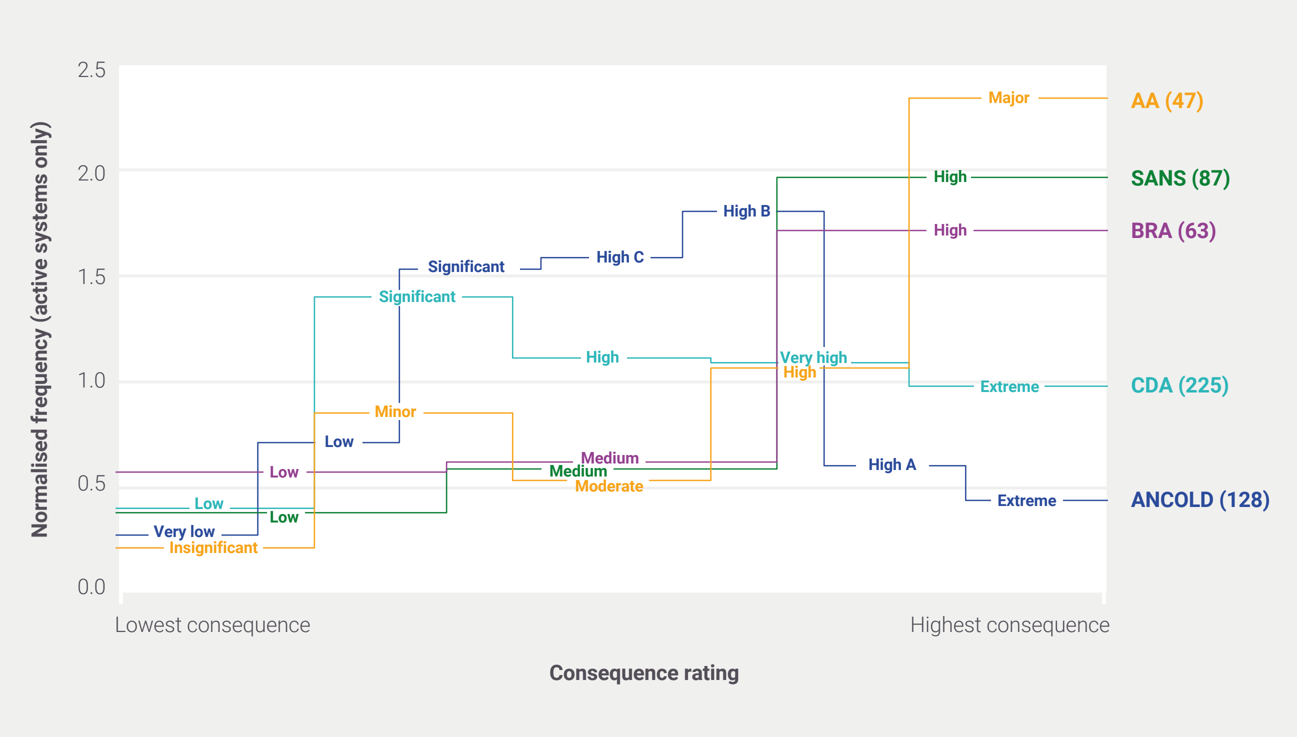

Figure 14. Distribution of active facilities by consequence rating for each of the five most common consequence classification schemes

Figure 15 reports consequence of failure by facility raise type for active facilities across the five most common schemes. A trend is apparent where hybrid, upstream, downstream and centreline facilities are more likely to be associated with higher consequence ratings than are dry-stack, single raise and in-pit/natural landform facilities. This general trend holds across each of the individual consequence schemes.

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[16] A small number of facilities reported against more than one scheme.
[17]. To allow fair comparison of the distributions, the frequency of the Y-axis is normalised so that the area under each consequence classification curve is the same.

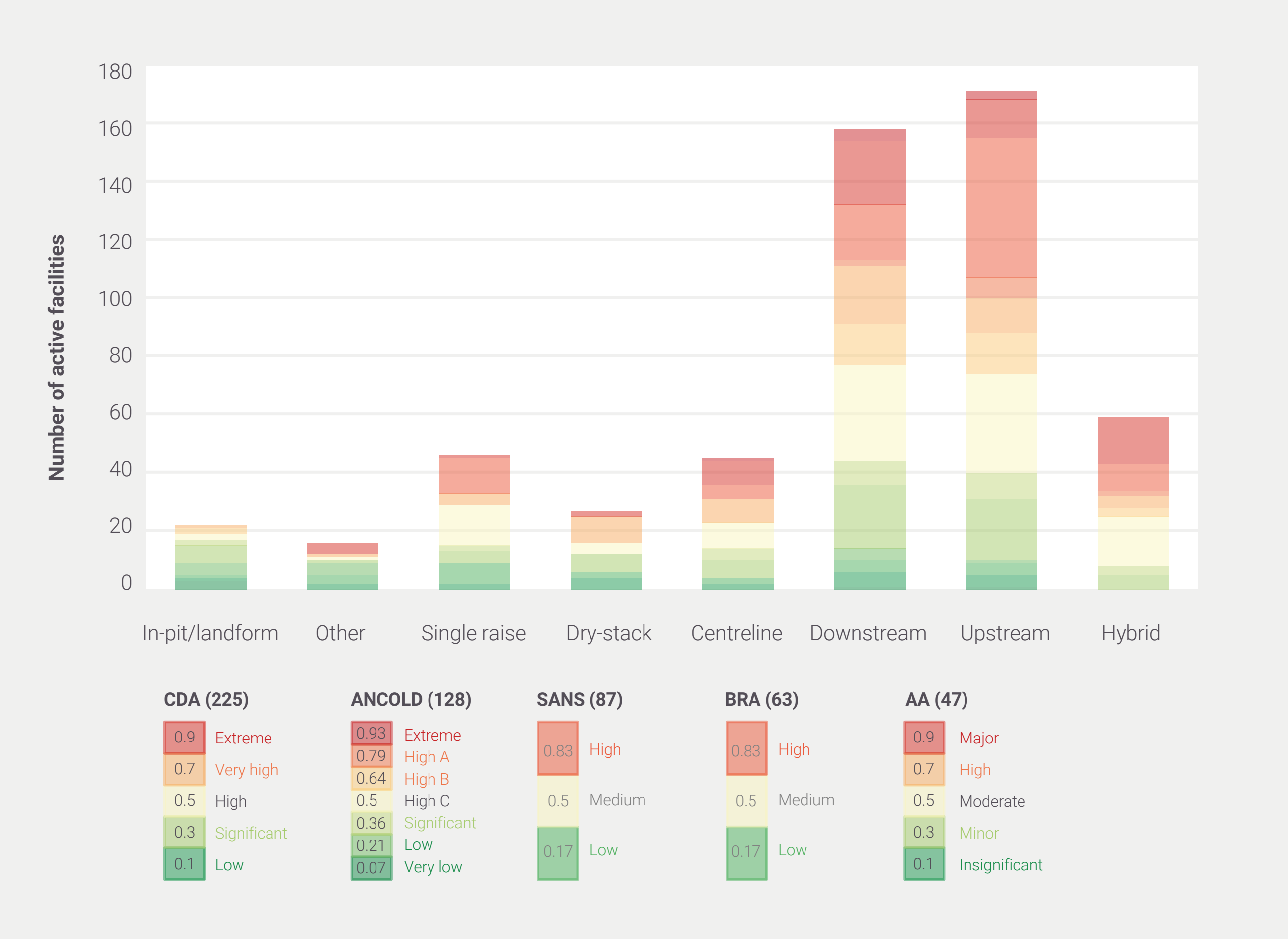

Figure 15. **Consequence of failure by facility raise type (active facilities) for five most common consequence classification schemes**

The associations in Figure 15 are influenced by at least two factors: (1) the nature of tailings flow (for example, hydraulically deposited tailings deposited in conventional facilities have a greater propensity to flow than filtered tailings that are deposited in dry-stack facilities); and (2) the decision on the selection of the construction method for different geographic circumstances (for example, a larger number of a particular type of facility may have been constructed in locations where the consequence of failure is higher). Given that upstream facilities have been considered by ICOLD and UNEP (2001) to be less safe than downstream and centreline facilities, it could be expected that the construction of these facilities would be avoided in locations where the potential consequence of failure is high. However, based on the data presented here, this does not appear to be the case.[18]

Figure 16 illustrates the likelihood of a past stability issue being reported within each consequence category for the five most common schemes. A trend is apparent across most schemes (with the exception of ANCOLD) where facilities that have been assigned a higher consequence rating are more likely to have reported a past stability issue. This finding is somewhat counter-intuitive as higher consequence facilities are expected to be built to higher construction standards, though it may in part be explained by the lower proportion of dry-stack and in-pit/natural landform facilities that are classified in higher consequence categories, which are also associated with a lower likelihood of past stability issues.

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[18] It should be noted that some jurisdictions (such as Chile, Peru and Brazil) have restricted upstream facilities due to a view that they hold a greater 'likelihood' of failure in their local operating conditions.

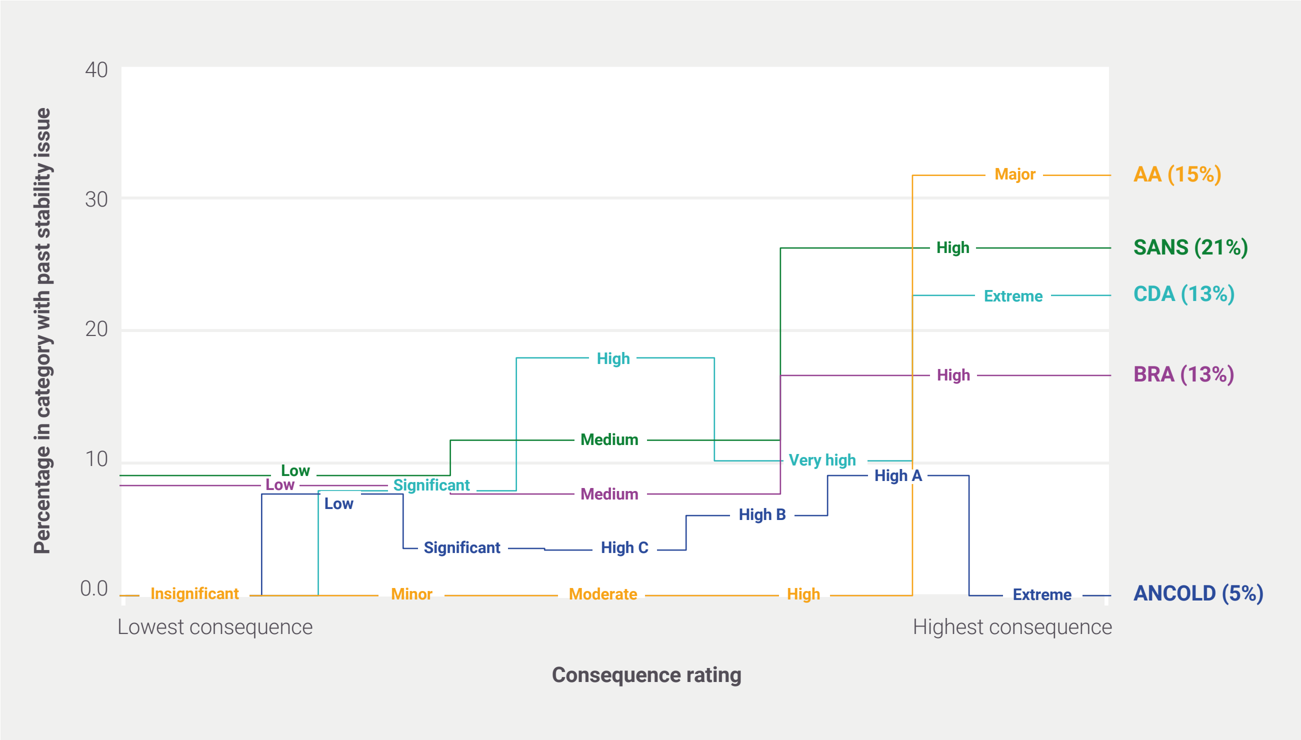

Figure 16. Proportion of sites reporting a past stability issue by consequence of failure five most common consequence classification schemes

Note: the overall percentage for each scheme is given in brackets.

3.6 UPTAKE OF DEWATERING TECHNOLOGIES

The removal of water from tailings is an important innovation that has been identified by a significant number of authors as having the potential to improve geotechnical and geochemical stability (Nguyen and Boger 1998; Boger 2009; Boger *et al.* 2006; Jewell and Fourie 2006; Davies *et al.* 2011; Franks *et al.* 2011; Edraki *et al.* 2014). Dewatering technologies have experienced a wave of different advances over the past few decades: cycloning in the late 1960s, tailings thickening in the mid-1970s, filtered tailings in the 1980s and paste facilities from the 1990s (Davies *et al.* 2011). When analysing the disclosures, it was not possible to differentiate paste and thickened tailings from wet tailings due to the fact that the former are also stored within conventional tailings facilities. Similarly, the dataset does not include details on the uptake of paste backfill because this type of waste is not stored in a 'facility' per se. Dry-stack facilities are identifiable in the dataset, however, it is worth noting that this categorisation includes both in-situ dewatering of tailings (sometimes referred to as mud-farming) and the filtering of tailings prior to deposition (beginning in the 1980s).

Dewatered tailings are commonly assumed to have increased in popularity over recent years, and have also been identified as a priority by individual mining companies and peak industry bodies. The data indicate that no more than 13 dry stack facilities were constructed in the last decade. Furthermore, since 1980, the percentage of new tailings facilities that are dry-stack has fluctuated between 4 and 6% (see Figure 17), indicating that the uptake of tailings filtration and in-situ dewatering has not significantly increased in recent decades.[19]

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[19] It is possible that uptake may have been slowed by the long lead times for new projects and the time taken for regulators to approve 'new' disposal methods. However, it seems very unlikely that these factors alone can account for what is effectively a flat line over the last two decades.

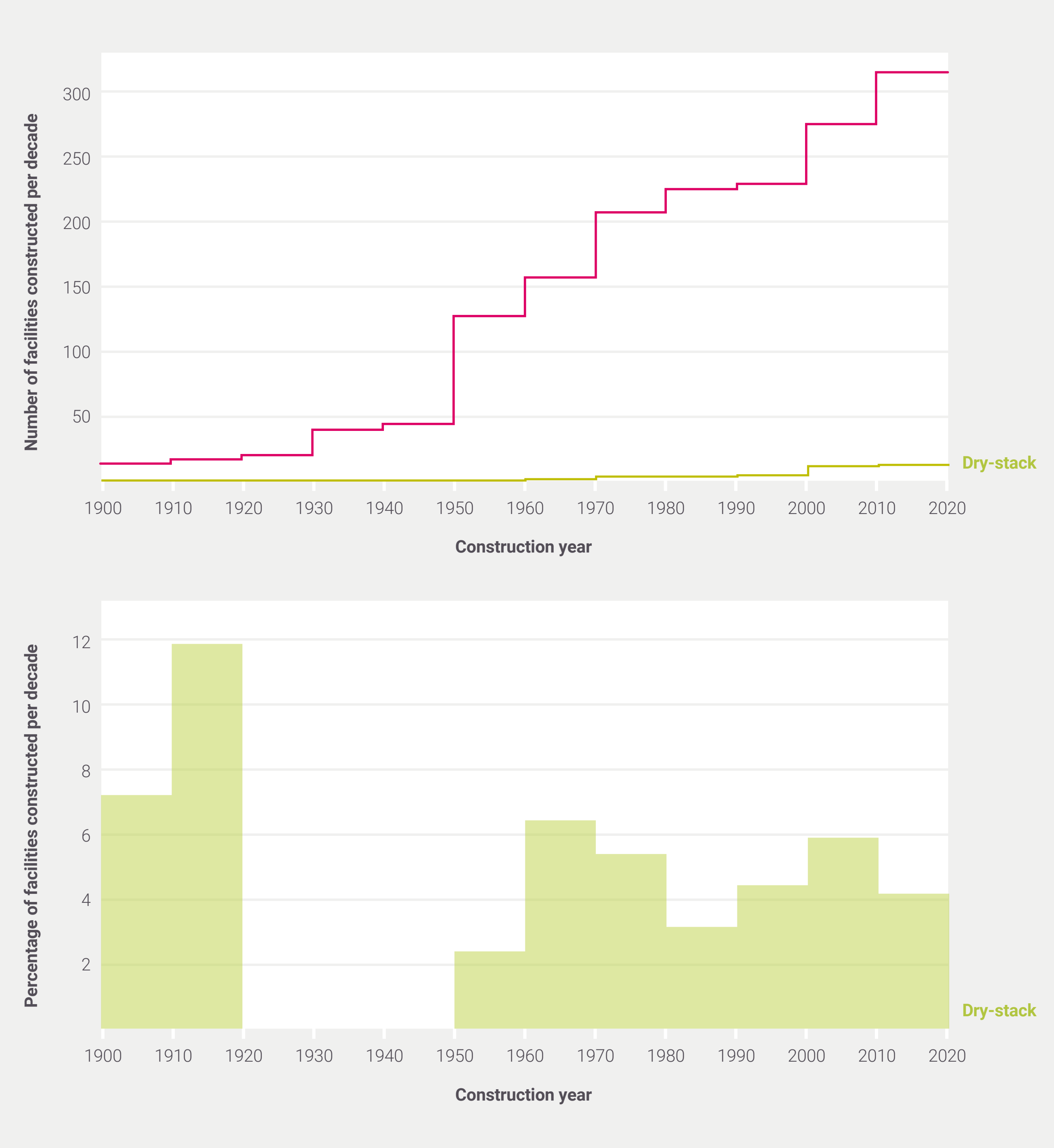

Figure 17. Dry-stack facilities by decade of construction

Note: Top graphic shows number of facilities; bottom graphic shows proportion of facilities.

This finding is further confirmed by the fact that just one international mining company operates, or is the majority shareholder in, 72 per cent of all dry-stack facilities. This raises a question about whether the economic and policy incentives to transition to these new technologies are sufficient, noting that performance factors also influence rate of uptake (e.g. production throughput, climatic considerations, dust generation) as does the regulatory context (permitting and approval processes).

4. CONCLUSION AND FUTURE DIRECTIONS

In this chapter we have undertaken an analysis of the features of global tailings facilities, utilising company provided data. The analysis demonstrates that the characteristics of tailings facilities are highly variable by construction type, geography and size. The findings point to the value of information disclosure by companies for understanding tailings facilities and their management.

The sheer scale of global tailings production, the expansion of tailings facilities over time, and the high impact of tailings facility failures highlights the need for more to be done on developing and implementing new tailings disposal and management approaches at scale and also on reducing the volume of tailings generated (see the review of alternative approaches to tailings management by David Williams, this volume).

More work is also required to understand and overcome barriers to innovation.

The findings presented here demonstrate some of the potential insights that can be generated from the current dataset, with further analysis of parameters such as climate and topography most obvious. Future disclosure requests can be refined with questions about the type of past stability issue, better breakdown of tailings production over time, indication of the type of operation (open-cut, underground etc.), date of closure of facilities, date of any past stability issue, better differentiation of tailings type (slurry, co-disposal, cycloned, thickened, paste and filtered), the presence of liners, seepage and seepage treatment, and reporting on the presence of paste backfill and other tailings management options that go beyond the definition of a 'facility.'

KEY MESSAGES

1. The Investor Mining and Tailings Safety Initiative, as described in Chapter XVII, conducted the most comprehensive global survey of tailings facilities ever undertaken. The trends identified from this dataset highlight the value of information disclosure by companies.
2. Analysis of company-disclosed data collected through the Initiative indicate that upstream facilities still make up the largest proportion of total reported facilities (37 per cent), although construction rates for upstream facilities have declined in recent years.
3. The rate of reported past stability issues for facilities in the data base exceeded one per cent for most construction methods, highlighting the universal importance of careful facility management and governance.
4. Over 10% of facilities in the database reported a stability issue, and the percentages for upstream, hybrid and centreline facilities were even higher. Statistical analysis provides a high level of confidence that the higher rate of reported stability issues for upstream facilities is not attributable to 'confounding' factors such as differences in facility age, the volume of material stored, or the level of seismic hazard.
5. Based on company commissioned modelling, hybrid, upstream, downstream and centreline facilities are more likely than other types of facilities to be associated with a higher consequence of facility failure.
6. Facilities with higher consequence of failure ratings were also more likely to report a stability issue.
7. Based on the data provided by companies, the uptake of filtered and in-situ dewatering of tailings across the wider industry has not significantly increased over recent decades. This is notwithstanding that dry-stack (and in-pit/natural landform facilities) report fewer past stability issues and are typically associated with lower consequence of failure ratings.

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