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TOWARDS PRO-ACTIVE REHABILITATION PLANNING OF WATER SUPPLY SYSTEMS

Balvant Rajani, Group Leader, Senior Research Officer and
Yehuda Kleiner, Senior Research Officer
Institute for Research in Construction
National Research Council of Canada, Ottawa, Ontario, Canada K1A 0R6

ABSTRACT

Making decisions on the renewal of a water distribution system is essentially a balancing act between system performance and costs. In water distribution systems three types of failure are observed, structural, hydraulic and water quality. Frequencies of these failures together with failure consequences define failure risk. Risk can thus be mitigated by a reduction of failure frequency, i.e., renewal, and/or limiting failure consequences.

Life-cycle cost comprises risk (or the expected consequences of failure), cost of renewal and reduction of failure consequences. Sound decision should minimise this life-cycle cost, but to achieve this goal one must be able to quantify risks.

In this paper the critical elements of a holistic view of water supply systems are identified and these are discussed in relation to the current state-of-practice and future research directions towards the pro-active planning of their renewal. While various models are available to analyse water main breaks, commensurate efforts need to be dedicated towards analyses of water quality and hydraulic failures.

Keywords

Distribution mains, transmission mains, rehabilitation, costs, hydraulic, water quality and, water mains failure frequencies.

INTRODUCTION

Making decisions on the renewal of a water distribution system (or any system for that matter) requires finding a balance between system performance and costs. What makes it so challenging is that it is often not known how to define and measure global performance, let alone decide what level of performance is acceptable. As well, the costs involved to achieve specific levels of performance are often not well defined or documented. It is fairly well known, however, what the distribution system must provide in terms of qualitative criteria:

- Provide all regular and peak demand for water at an acceptable pressure, with minimal or no interruptions.

- Be capable of providing emergency flows (e.g., for fire fighting) at an acceptable pressure.
- Provide safe drinking water.
- Provide water that is acceptable to the consumer in terms of aesthetics, odour and taste.
- Be economically efficient.

It is also known that the costs involved in a water distribution system comprise:

- Capital investment in system design, installation and renewal.
- System operation – energy, materials, labour, monitoring, etc.
- System maintenance – inspection, breakage repair, etc.
- External costs resulting from failure, such as property damage, disruption, illness, etc.

Putting all these issues together in a single decision framework has proven to be very challenging because first, all the mechanisms affecting the above performance criteria are not understood, and in addition, the spatial and temporal variability of even a moderate-size system makes it a difficult problem to solve.

In this paper an attempt is made to provide a holistic view of all issues related to the decision making process for renewal planning of water distribution systems. Existing research is identified and how it may fit into this holistic view, and areas where further research is needed are highlighted. The few references provided were selected to demonstrate the point made, and constitute only a fraction of the relevant body of work that is available in the literature.

FAILURE RISK IN A WATER DISTRIBUTION NETWORK

A distribution system can fail in more than one way. If failure is broadly defined as the inability (momentary or extended) to meet performance criteria, then modes of failure could include any pressure drop below a specified minimum, any unscheduled service disruption, any event of water safety breach, water aesthetic complaints, etc.

Figure 1 depicts the authors' view of the general framework for making comprehensive decisions regarding the renewal of water distribution systems. As pipes age they deteriorate. This deterioration manifests itself in an increasing breakage and leakage rate as well as increasing internal roughness. The increased internal roughness affects both the hydraulic capacity and the water quality in the pipes. Deteriorated inner pipe surfaces may harbour and encourage bacterial regrowth. Leaky pipes also affect both the hydraulic capacity and the water quality in the distribution system. Leaks increase flow demands and provide a pathway for contaminants to intrude into the network when pipes are de-pressurised for repair or maintenance. Frequent breaks thus also contribute to the likelihood of contaminant intrusion.

In the context of reliability engineering and risk management, the definition of risk depends on the type of asset or system (Henley and Kumamoto, 1981). For buried pipes one can define the risk of any type of failure as the expected magnitude of the consequences of failure(s), i.e.,

$$\text{Risk of failure} = E(\text{failure consequence}) = f(\text{probability of failure, costs of failure}) \quad (1)$$

In the following discussion the terms rehabilitation, renewal, and replacement are simply referred to as renewal for the sake of brevity.

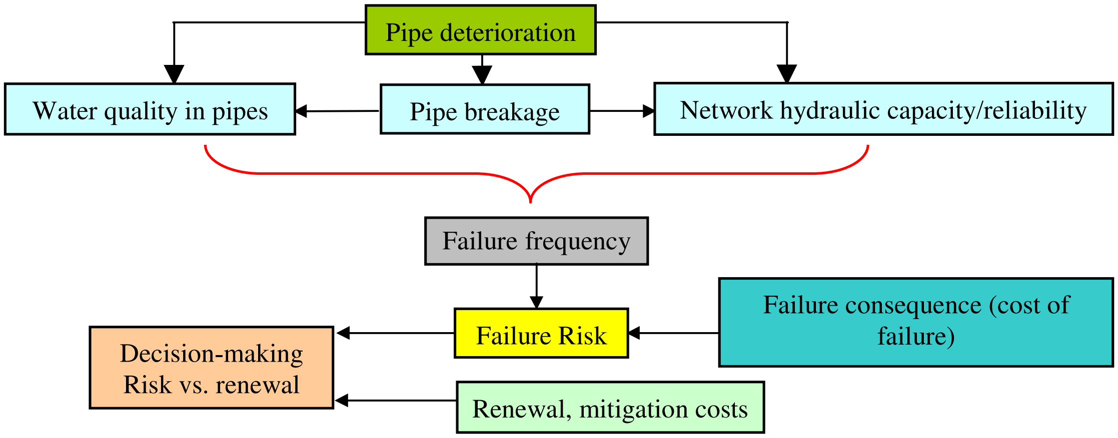

Fig. 1. A general framework for decision making in water distribution system.

DEFINITION OF FAILURE

Discussion on probability of failure in water distribution systems must be preceded with the definition(s) of failure. Physical rupture of a water main is fairly easy to define, i.e., “break” or “burst” failure where an active repair intervention is required. Hydraulic failure is usually defined as the inability of the network to supply demand at minimum pressure (e.g., Bouchart and Goulter, 1991). Hydraulic failure can occur due to one or more of the following: (a) demand is greater than that for which the system was designed (leaks can be defined as demand as well), (b) a component in the network fails, (c) deterioration of pipes inner surfaces diminishes the network’s hydraulic capacity.

The reliability of a water distribution network has received numerous definitions in the literature (e.g., Wagner et al.,1988a, 1988b; Cullinane et al., 1989; Goulter and Bouchart, 1990; Fujiwara and De Silva, 1990; Quimpo and Shamsi, 1991, and others). Invariably, network reliability is a hybrid measure affected by the network topology (redundancy) and its hydraulic capacity. The multitude of reliability definitions naturally makes it more difficult to define a reliability failure.

Water quality failure is by far the most difficult to define and quantify. The numerous ways in which water quality failures can occur in the distribution network can be broadly classified into four categories: (a) intrusion of contaminants into the distribution system through components whose integrity was compromised or through ageing or misuse, (b) regrowth of bacteria in components of the system, (c) leaching of chemicals or corrosion products from system components into the water, and (d) permeation of organic compounds through system components into the water. It can be argued that the first category is in fact a water quality event which is the consequence of a structural failure of a network component rather than an independent water quality failure. The following section that details failure costs subscribes to this argument.

One can further classify water quality failures (and/or events) by the severity of their consequences, i.e., water aesthetics vs. water safety. The spatial variability of the distribution network and the fact that most water quality events are not detected in real time often make it very difficult to model or even validate the exact cause of a water safety failure. Water aesthetic failures (indicated by customer complaints) are usually addressed by a lengthy process of elimination that may include network modelling and systematic examination of components at, or upstream of, the failure location.

The lack of consensus on what constitutes a failure often leads to poor record keeping practices. Much research needs yet to be done to define all the different types of failure and how these should be documented. Subsequently, studies of failure causes and frequencies can be undertaken in a more rigorous way.

CONSEQUENCE (COST) OF FAILURE

The costs of a water main failure event may be classified into three categories: (a) direct, (b) indirect, and (c) social costs.

(a) Direct costs to the water purveyor:

- Breakage repair (affected by pipe type, size, type of break, pipe location, etc.),
- lost water (affected by the pipe size and the severity of the failure),
- direct property damage, e.g., basement flooding, road cave-ins, foundation damage, etc.,
- liabilities, e.g., death or injury from traffic accident caused by flooding, electrical shock, etc.

(b) Indirect costs:

- loss of production and or business in industrial or commercial properties due to water outage,
- accelerated deterioration of trenches, roads, sewers, underground cables, etc.,
- losses due to fire that could not be effectively extinguished due to water outage (in the immediate vicinity) or diminished hydraulic capacity (elsewhere in the system).

(c) Social costs:

- adverse effects of pipe failure on water quality due to intrusion of contaminants into a pipe that was de-pressurised for repair,
  - intrusion of contaminants from surrounding soil (e.g., leaky sewers, waste disposal sites, etc.) through corrosion holes and leaky gaskets in de-pressurised segment of the system,
  - increased likelihood of backflow due to cross-connection into de-pressurised segment of the system,
  - debris intrusion through broken pipe,

  consequences may be discomfort, illness or even loss of life, e.g., Chicago, 1939 where 98 died and 1409 people contracted amoebic dysentery,
- service disruption (quality of life, public confidence),
- traffic and business (affected by the location of the failed pipe) disruptions,
- service disruptions to special facilities, e.g., hospitals, schools, etc.

Hydraulic and water quality failures that are not related to pipe structural failure carry costs that are mainly in the realm of indirect or social costs, e.g., loss of production, fire extinguishing, quality of life, etc. It can also be said that generally, one cannot spot-repair a hydraulic or a water quality failure in the same sense that a ruptured pipe is repaired. A hydraulic and a water quality failure usually point to deficiencies that have to be addressed on a wider scale, such as cleaning, scrubbing, lining (non-structural) or out-right replacing various components of the network. In some cases operational changes (e.g., ortho-phosphate) are required. In the context presented here, the cost of these remedies cannot generally be considered failure costs, but rather as renewal (lining, replacement) or maintenance (flushing, ortho-phosphate) costs.

While direct costs are relatively easy to quantify in monetary terms, indirect costs may require much more effort, and social costs are often the most difficult to describe and assess. Further, the magnitude of failure consequence is, strictly speaking, a random value because no two failures have the same consequences. Failures in small distribution mains are usually repaired with little effort and typically collateral damage is relatively small. Failures of large transmission mains are relatively rare, and because only few water utilities attempt to assess total failure damage there are currently insufficient data to assign probability distributions to failure costs. The consequences of hydraulic failures are rarely assessed, except when fire liability is concerned. The consequences of water quality failures receive increasing attention because of media exposure, but rigorous assessments are yet to be published. More research is required to gain a better understanding of the true magnitude of indirect and social consequences of all failure types.

PROBABILITY OF FAILURE

The probability of failure can be assessed in different ways, some more rigorous than other, depending on the type of failure and on the available data.

The probability of a water main failure due to structural deterioration can be estimated using mechanistic models that compare stresses acting on a pipe to its residual strength. The main problem with these models (assuming robust comprehensive models) is that they require a lot of data that are either unavailable or very costly to obtain, for even a modest portion of a distribution network, because of spatial variability. Repeated condition assessments, using non-destructive evaluations (NDE) techniques, can assist in the calibration of some of the parameters of these models, and improve their accuracy. Alternatively, a more manageable approach is to develop empirical relationships between the pipe, its exposure to the external and operational environments and its observed failure frequency. These empirical models typically over-simplify a complex reality in order to achieve "80% of the answer with 20% of the effort". This goal of 80-20 is not always achieved because of over simplification or because of insufficient historical failure data.

It should be noted that some water main failures such as those caused by accidental or malicious third party interference cannot be assessed with either of these approaches. These may require qualitative-quantitative approaches such as fault trees, or actuarial type calculations.

The availability of fast and robust water network simulation programs has facilitated the ability to calculate the probabilities of hydraulic failures. However, difficulties still remain with issues such as calibration of roughness coefficients, modelling and predicting demand variations, and modelling and predicting the deterioration of roughness coefficients due to tuberculation and corrosion and their spatial and temporal variations.

The probabilities of water quality failures in the distribution system have yet to be addressed in a rigorous manner. The complexity of the mechanisms leading to some of these failures, exacerbated by the spatial and temporal variability in the physical state of the pipes as well as the systems boundary conditions (physical environment, efficacy of treatment, etc.) makes direct physical modelling very challenging. Vasconcelos et al. (1996) modelled the depletion of residual chlorine as a surrogate measure for the biochemical state of water but the results obtained were mixed.

Ofsted and Shamir (1996) and others attempted to model the propagation of contaminants from multiple sources through the distribution system but did not address the deterioration of water quality in the pipes. Water safety failures that are related to the distribution system are relatively rare and even so are believed to be under-reported. Available data permit only actuarial-type frequency analysis or application of a qualitative-quantitative approach.

RISK OF FAILURE

Risk mitigation can be achieved by either reducing both failure probability and/or its cost, as risk depends both on the probability and the cost of failure (equation (1)). As the distribution system ages, its components deteriorate and the probability of failure increases. This is true for structural failure as well as for hydraulic failure and many types of water quality failures. In some cases, it can be argued that the cost of failure is also likely to increase over time, for example, when a pipe is located in a rapidly developing area, but generally it is assumed that failure cost is not time-dependent.

Measures to mitigate risk from the cost side are possible but rather limited in scope. Examples include: Timely response by a well-trained pipe repair crew will reduce the cost of repair as well as water loss and collateral damage resulting from a main brake. A good monitoring program will initiate a fast action to communicate to the public any water safety failure, thus minimising the level of exposure to the low quality or unsafe drinking water. An adequately sized storage tank will reduce the vulnerability of a hospital to a hydraulic failure.

It appears that mitigating risk on the failure frequency side has a greater potential because theoretically, one can reduce failure frequency to nearly zero (thus reducing risk to nearly zero) albeit at a very high cost. It follows that a rigorous decision process should find a balance between the risk of failure and the cost to mitigate it. Figure 2 illustrates this concept. As long as the pipe continues to age and deteriorate without renewal, its probability of failure (or failure frequency) increases and the risk increases as well (note that here the risk is expressed in discounted expected cost). At the same time, as pipe renewal is delayed, its discounted cost (or present value) declines.

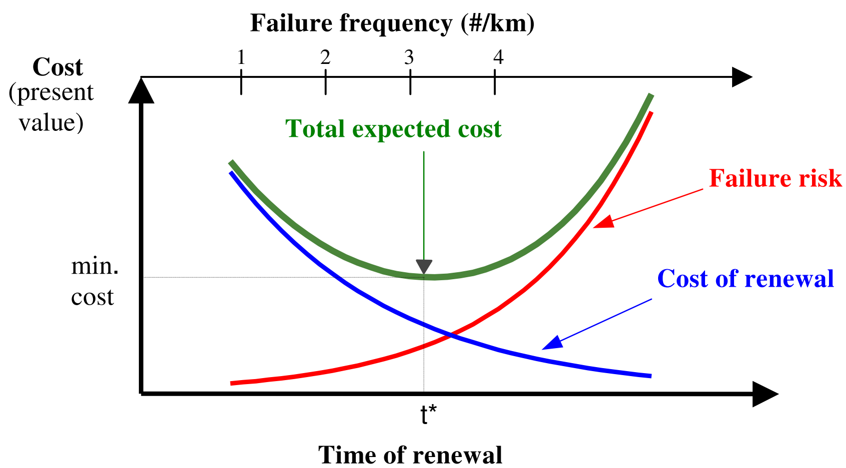

Fig. 2. Deciding when to renew a water main with a low cost of failure.

The total expected life-cycle cost is the sum of the total expected cost of failure and cost of renewed pipe. The total expected life-cycle cost curve typically forms a convex shape, whose minimum point depicts the optimal time of renewal (t^*). This point also depicts the time at which the marginal decrease in the discounted cost of renewal equals the marginal increase in the discounted expected risk – this is the balance mentioned above between the risk of failure and the cost to mitigate it. The same type of analysis can be done to include risk mitigation on the failure consequence side. A similar balance should be sought between the investment required to reduce failure consequence (e.g., build a storage tank in a hospital, or an advanced monitoring system) and the reduction in risk it might achieve.

The top horizontal axis of the graph in Figure 2 indicates that the optimal renewal time is obtained at a failure frequency of about 3 events per unit length. This represents a typical case of structural failure in small diameter distribution mains, where a given threshold of breakage frequency can be tolerated because the cost of failure is relatively low. This means that the preferable strategy in this case is to pursue *failure management* (frequency of occurrence) rather than attempt to prevent failure altogether.

In Figure 2 the curve depicting total cost is deeply convex with a clear minimum point at $t*$. This is a rather idealised case, which may change in some cases. When ageing rate (i.e., the rate at which failure frequency increases) is similar in magnitude to the discounting factor, the convexity of this curve can become quite flat, and the point of minimum cost becomes less crisp. When the cost of failure is relatively low compared to the cost of renewal and the discounting factor relatively high, the curve can take the shape of the "hammock-chair" as described by Herz (1999), with no definite minimum, indicating that renewal should perhaps be postponed indefinitely.

Two points should be highlighted with respect to the convexity of the total cost curve. First, taking into consideration the entire cost of failure, including direct, indirect and social costs, will reduce the ratio between the cost of failure and the cost of renewal, which will push the point of minimum towards earlier renewal and increase the convexity of the total cost curve. Second, The discounting factor used should be a social discounting factor, which is invariably lower than a financial one. The social discounting factor can be perceived as a means to distribute available resources over time, or in other words "...discounting acts to distribute benefits today, paid for tomorrow" (Swartzman, 1982). Consequently, the selection of the discount rate reflects the political and ethical attitudes of the decision-maker. The deeper the discounting the more we would tend to reap benefits today and let future generations pay. Selecting a relatively low discount rate will push the point of minimum towards earlier renewal and increase the convexity of the total cost curve.

Figure 3 shows the case of large transmission mains where the ratio between the cost of failure and the cost of renewal is significantly smaller. The optimal renewal timing is at a very low failure frequency. This means that it might be economical to take extra measures (and incur extra expense) to try and anticipate imminent failures in order to prevent them before they occur.

With regard to structural failures, when the cost of failure is relatively low and failure frequency can be tolerated, it is often (but not always) sufficient to rely on empirical models using historical breakage patterns to predict future failure rates. However, high failure costs may justify the use of extra measures to anticipate failures and prevent them in a proactive approach. These measures could include inspection and condition assessment using NDE techniques in conjunction with physical/mechanical models. Non-destructive evaluations techniques can be used on two levels:

first, as a snapshot of the pipe condition at a given time in order to determine if immediate intervention is required, and second, using subsequent inspections to determine the rate of deterioration. It is inevitable that the costs of applying NDE techniques will decrease, as they become widely available. Consequently, their use will become economically viable for larger portions of the distribution system, until eventually all water mains will be periodically inspected by NDE techniques.

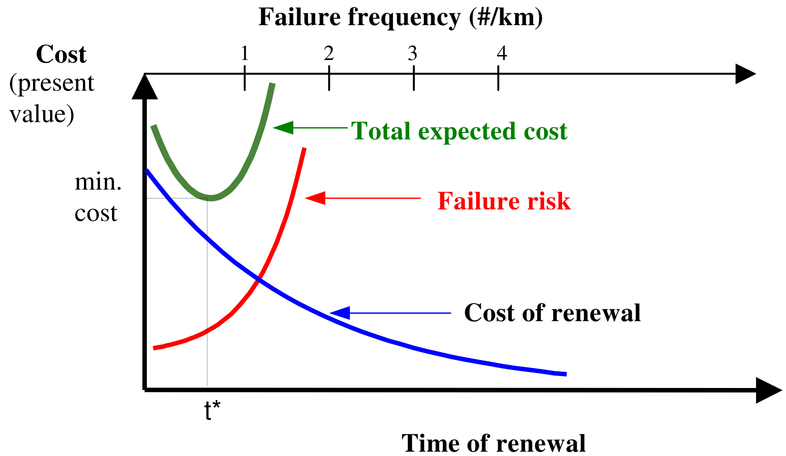

Fig. 3. Deciding when to renew a water main with a high cost of failure.

MAKING DECISIONS FOR WATER MAIN RENEWAL

Plainly stated, the decision objective is to minimise the total life-cycle costs of the system, where life cycle costs include operations, maintenance, renewal and failure costs. This, of course, is easier said than done, because of all the uncertainties described in the earlier sections and because some of the failure costs are non-commensurate with others (e.g., people infected in an outbreak resulting from a water safety failure). There are various techniques to address multi-objective decisions. Some are simple, such as the point-scoring method, others more elaborate such as utility matrices. While the former type is often overly simplistic and is prone to personal bias, the latter is often too cumbersome to apply to a system with such a high level of complexity. An alternative approach could be to formulate it as a traditional optimisation problem. Cast in this form, the optimisation criterion is minimum cost while all other objectives and criteria that cannot be assigned monetary values are taken into consideration as constraints, e.g.,

Minimize: {capital costs + operation costs + maintenance costs + renewal costs}

Subject to:

- *supply pressure head boundaries (i.e., minimum and maximum residual pressure head)*
- *minimal level of reliability constraints*
- *minimal level of water quality constraints (some dictated by regulations)*

However, this approach does not really solve the difficulty, because in the strict mathematical sense treating a factor as a constraint is equivalent to assigning an infinite cost to it. We all know that in the social sense there is no such thing as infinite cost, even for human life (would a decision

-maker expend billions of dollars to save a life?). Subsequently, a prudent analysis will include sensitivity analyses of shadow prices to determine how much the objective function (life-cycle cost) would change if the level of a constraint is changed. In consequence, through making certain choices the decision-maker, either explicitly or implicitly, assigns monetary values to all cost components.

Regardless of the route chosen to formulate this decision process, any attempt to solve this problem comprehensively and rigorously would currently be overly ambitious in light of available knowledge and computational tools. A piece-wise approach seems to be warranted and indeed has been attempted. Kleiner (1997) and Engelhardt et al. (2000) described most of these attempts.

FINAL REMARKS

Despite inherent complexities, the industry generally seems to be going in the right direction, as more and more understanding is gained about deterioration processes and failure modes. At the same time, as practices change and new materials are used, the knowledge gap, while decreasing from one end is increasing from the other.

As non-destructive evaluations (NDE) techniques evolve, including the development of various sensors and robots, it appears that failure anticipation and prevention is likely to become more technologically feasible as well as affordable. Currently, it seems that only mains prone to high-cost failure (namely transmission mains) can justify these techniques, but over time this would likely change.

In the meantime, while the bulk of water distribution network comprised of small mains with relatively low failure consequence, NDE techniques can be, in some circumstances, used to complement empirical models, which rely on historical break records. However, more research is required to interpret NDE results in a way that they can be used in conjunction with empirical models to gain a better ability to predict pipe deterioration rates.

As for the empirical models, efforts dedicated to estimating the frequency of water mains breaks have been significant as evidenced by the numerous models (time-linear, time-exponential, proportional hazard, accelerated lifetime, cohort survival, etc) available. It seems however, that the industry is lagging in translating these models into useable decision tools and that most utilities still don't use these models in a rigorous way. It is hard to tell whether the lack of use is the result of lack of tools or visa versa. Perhaps the reason is that the perceived accuracy of these models is low. Most of the available models allow only for the use of the so-called static covariates, i.e., they consider the effect on breakage rate of factors such as pipe type or size. This implies that the pipe is affected by factors that do not change over time. As the life of water mains is measured in decades and even centuries, this implication is generally false. Environmental (e.g., climatic) changes as well as operational changes, are known to affect the breakage rates of pipes and thus need to be considered in these models, to gain a better understanding as to the true deterioration rate of the pipe. We also need to question whether added mathematical complexity and the associated efforts required for its implementation in a proposed model provides a "better" prediction of failure frequency.

Water quality failures in the distribution network require yet much research. Water quality events as a consequence of structural failure will likely be treated as qualitative-quantitative hazards because they depend on the presence of contaminants external to the distribution system, which cannot be modelled within the same framework. However, phenomena that are intrinsic to water mains such as bacterial regrowth require more research. This research is likely to accelerate when real-time sensors are available to continuously monitor networks.

With the existence of network simulators, hydraulic failures are not difficult to model through simulations (e.g., Monte-Carlo simulations) with probabilistic inputs. There is, however, a computational difficulty in combining hydraulic failures with other types of failure or to make long-term forecasts on the hydraulic performance of ageing networks. Because many simulations are required to quantify the probability of each hydraulic failure, and many hydraulic failures are required to combine hydraulic reliability measures with long-term planning models, this may require significant computational resources. Approaches such as network skeletonisation or surrogate hydraulic reliability measures may alleviate this limitation.

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