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Seismic reliability assessment of water distribution network considering probable leakage in each link using informational entropy

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ABSTRACT

The present study aimed to propose a modified criterion based on the concept of informational entropy to evaluate the seismic performance of water distribution networks. Using the concept of dissipated power, the original entropy function was modified in such a way to calculate the network entropy value considering both mechanical and hydraulic characteristics of the network. To consider both mechanical and hydraulic characteristics, a new weighting ratio was defined as the outflow value at each node divided by the total dissipated power in the network. Finally, the original weighing ratio was replaced with this new one. Moreover, to calculate the network entropy value in view of possible leakages in all links, the entropy function defined in the previous stage was re-modified by taking into account both the value and place of the leakages in all links, and the entropy value of the hydraulically balanced network after the leakage occurrence was determined. The proposed entropy function was used to calculate the entropy value of several sample networks with leakage. The results proved that it is efficient in evaluating network serviceability, identifying the most important link under various hazard scenarios, and devising plans for mitigating the effects of damages caused by a wide range of hazards.

1. Introduction

Seismic performance of water distribution networks has recently drawn great attention, and much has been done to improve the seismic performance evaluation methods for these networks. In one of the earliest studies, Shinozuka et al. (1981) developed a method to assess the seismic risk of the pipeline transmission system in Los Angles in terms of the degree of serviceability. Isoyama and Katayama (1981) suggested a simulation method for evaluating the microscopic performance of Tokyo water supply system during the post-earthquake period using possible flow method. O'Rourke et al. (1985) simulated the serviceability of seismically damaged water supply systems in the city of San Francisco. In addition, Hwang et al. (1998) performed a hydraulic simulation analysis to assess the serviceability of the water supply system in the city of Memphis. Also, Javanbarg et al. (2006) proposed a hydraulic simulation method, based on flow rate analysis, for two types of pipe damage states, namely, leakage and breakage. They evaluated the serviceability of the Osaka City water distribution network to ten hospitals. Their results indicated that the flow analysis may lead to a more realistic method for evaluating the seismic vulnerability of water supply systems. Javanbarg and Takada (2006) also considered redundancy as a reliability measure which could be determined to evaluate the seismic performance of a water distribution system from three points of view: first, redundancy could be evaluated along with reliability assessment of system performance, second, redundancy could be effectively used in designing new networks so as to choose the best alternative in the earthquake-proof design of a distribution network, and third, for the seismic mitigation in an already-made network, it is worthwhile to have a measure for finding the best strengthening procedure of damage mitigation.

Reliability of a water distribution network can be defined as the probability of demand nodes in the system receiving sufficient supply with satisfactory pressure head (Mays, 1989; Esmaili and Hamilton, 2014; Hampton, 2014). Redundancy in a water

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distribution network implies the reserve capacity of the network, and the demand nodes have alternative supply paths in case links fail in providing the desired service (Awumah et al., 1991). Seismic performance of lifeline networks during the past earthquakes has revealed that a single redundancy can increase reliability significantly. In other words, networks with some amount of redundancy have more ability to respond to partial network failures (Javanbarg and Takada, 2006).

Redundancy has been extensively studied by Awumah et al. (1991) and Kalungi and Tanyimboh (2003). Awumah et al. (1990, 1991) proposed the use of Shannon's entropy function (Shannon, 2001) for the first time as a surrogate measure for the assessment of water distribution networks reliability. Later, Tanyimboh and Templeman (1993) proposed a more suitable definition of the entropy function for water distribution networks by using a multiple probability space model and the conditional probability of Khinchin (1953).

Hoshiya and Yamamoto (2002) and Hoshiya et al. (2004) proposed a redundancy index in regard with the entropy of an event of damage modes conditioned on system damage. In the latter, a case study was carried out on physical damage simulation of Kobe city water network to find a strengthening measure against earthquake risks. However, in the later studies, the physical connectivity of system was considered as an effective parameter in redundancy analysis which does not necessarily reflect the functionality of the system. Based on the concept of information entropy, Javanbarg et al. (2007) also presented a quantified measure of redundancy in water supply networks considering both breakage and leakage states of damage within seismically damaged systems.

It is worth mentioning that Tanyimboh and Templeman (1993) did not take into account in their definition of entropy function, the differences between branching-tree networks having different layouts and the same number of supply and demand nodes which all have the same path entropy method (PEM) diagram. To overcome this problem, Hosseini and Emamjomeh (2014) introduced a penalty number for each link, which is equal to the amount of water loss in case of its failure, based on which a new weighting factor was suggested. In their entropy function the order of the demand nodes in the network was considered by introducing a new coefficient based on discharge ratios. They considered failure probability of the network links in the entropy function by defining a penalty function based on failure probability of the links in any hazard scenario, and inserted this penalty function in the original network entropy function.

It should be noted that previously defined entropy functions for water distribution networks in the literature are generally based on only the hydraulic characteristics of the network, i.e., they do not consider both the hydraulic and mechanical characteristics in their calculations. This is while network risk is highly affected by both of these characteristics. In the entropy function proposed by Hosseini and Emamjomeh (2014), breakage state of the links was taken into account. However, no attention was paid to the leakage effect in entropy function directly. Therefore, the present study has been conducted aiming to suggest a method for calculating the entropy value of the network which can take into account both mechanical and hydraulic characteristics of the network as well as both the amount and the location of possible leakages in each link. The proposed method not only evaluates network serviceability state which is hydraulically balanced after the leakage occurrence but also can effectively help to consider an optimal plan for repairing and renovating the damaged network.

2. Deficiency of the existing entropy function for water distribution networks

The formulation of the entropy function mainly relied on Shannon's measure of uncertainty (Shannon, 2001), which is an underlying principle of the information theory. Tanyimboh and Templeman (1993) were the first to establish the proper entropy function by using a multiple probability space model and Khinchin's conditional probability (Khinchin, 1953).The available network data are the topological layout, the value of supply and demand at all nodes, and the flow direction in each link. It is noteworthy that the flow direction in each link is a key assumption as there will be a maximum entropy flow distribution for each set of flow directions. The network entropy function developed by Tanyimboh and Templeman (1993) is as follows:

$$\frac{S}{K} = S = S_0 + \sum_{n=1}^{N} P_n S_n \tag{1}$$

where S is the entropy defined by Shannon, N is the total number of nodes, and K is the Boltzman constant which is usually set to unity. The entropy of the external inflows, S_0, is represented by:

$$S_0 = -\sum_{i \in I} P_{0i} \ln P_{0i} \tag{2}$$

where I is the set of all source nodes, and

$$P_{0i} = \frac{q_{0i}}{T_0} \tag{3}$$

where q_{0i} is the external inflow at source node i, and T_0 is the total supply or demand of the network.

The second term in the entropy function, expressed by Eq. (1), consists of the outflow entropy at each node, S_n, weighted by the P_n ratio, which is equal to the total outflow of each node to the total inflow of the whole network, which is:

$$P_n = \frac{T_n}{T_0} \tag{4}$$

where T_n is the total outflow at node n. An important point in the definition of outflow is that it is inclusive of any demand at the node. In Eq. (1), the outflow entropy at each node, S_n, is given by:

$$S_n = -\sum_{nj \in ND_n} P_{nj} \ln P_{nj} \tag{5}$$

where ND_n is the set of all outflows from node n, and

$$P_{nj} = \frac{q_{nj}}{T_n} \tag{6}$$

where q_{nj} is the flow from node n to node j. Entropy function in Eq. (1) shows that the entropy of a water distribution network has two components. The entropy of the external inflows, S_0, as the first component, is the uncertainty faced by a water molecule moving from the super-source to the individual supply nodes. This term is non-zero for multiple-source networks and zero for single-source networks. Moreover, the second part consists of the weighted entropy values at every demand node. It should be noted that, as it is seen in the formulae presented above, length, diameter, and roughness of the network's links are not used directly in Tanyimboh and Templeman (1993) formulation. Furthermore, their formulation does not consider the effects of connectivity state and order of the network's nodes to the source node, while these factors particularly determine the functional sensitivity of a network.

To add these effects in entropy function, Hosseini and Emamjomeh (2014) defined a penalty value T_P for each link, which is equal to the value of loss in case of its failure. Based on these penalty values, they introduced a new weighting factor P'_n as follows:

$$P'_n = \frac{T_n}{T_P} \tag{7}$$

where T_P is the summation of penalty values for all links in the network. They used this weighting factor instead of the previous one, P_n in Eq. (1), in the calculation of networks' entropy values, while the rest of the calculations were the same as Tanyimboh and Templeman (1993) calculations. To show the positive effect of the proposed parameter the simple water distribution network, shown in Fig. 1, was considered.

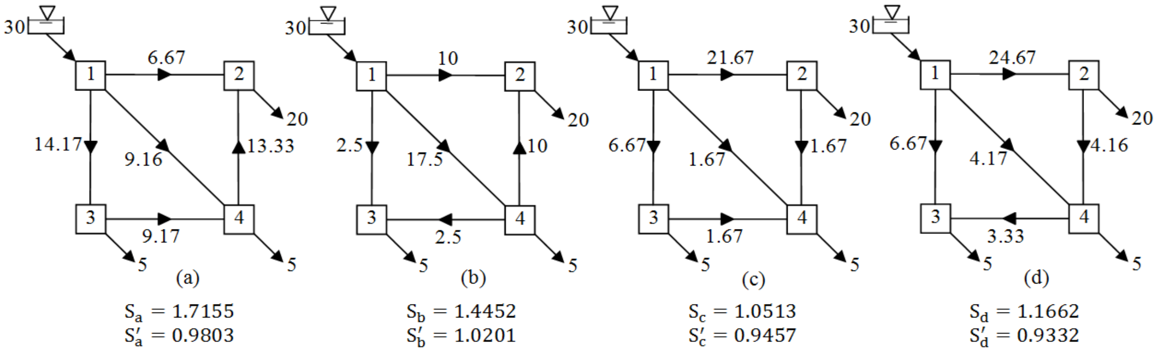


Fig. 1: Four different possible flow directions in the network and the entropy value using Tanyimboh and Templeman (1993) function *(S)* and its modified version proposed by Hosseini and Emamjomeh (2014) *(S′)*

Fig. 1 shows the entropy value for each network based on Tanyimboh and Templeman (1993) entropy function and its modified version by Hosseini and Emamjomeh (2014). As a sample of entropy calculations, entropy values of network (a) once by using Tanyimboh and Templeman (1993) function *(S)* and once more by Hosseini and Emamjomeh (2014) modified function *(S′)* are obtained as follow:

$$S_a = -\frac{30}{30}\left[\frac{6.67}{30}\ln(\frac{6.67}{30}) + \frac{14.17}{30}\ln(\frac{14.17}{30}) + \frac{9.16}{30}\ln(\frac{9.16}{30})\right]$$
$$-\frac{14.17}{30}\left[\frac{5}{14.17}\ln(\frac{5}{14.17}) + \frac{9.17}{14.17}\ln(\frac{9.17}{14.17})\right]$$
$$-\frac{18.33}{30}\left[\frac{5}{18.33}\ln(\frac{5}{18.33}) + \frac{13.33}{18.33}\ln(\frac{13.33}{18.33})\right] = 1.7155$$

$$S'_a = -\frac{30}{52.5}\left[\frac{6.67}{30}\ln(\frac{6.67}{30}) + \frac{14.17}{30}\ln(\frac{14.17}{30}) + \frac{9.16}{30}\ln(\frac{9.16}{30})\right]$$
$$-\frac{14.17}{52.5}\left[\frac{5}{14.17}\ln(\frac{5}{14.17}) + \frac{9.17}{14.17}\ln(\frac{9.17}{14.17})\right]$$
$$-\frac{18.33}{52.5}\left[\frac{5}{18.33}\ln(\frac{5}{18.33}) + \frac{13.33}{18.33}\ln(\frac{13.33}{18.33})\right] = 0.9803$$

It is expected that the reliability of the networks shown in Fig. 1 has a decreasing trend from (a) to (d), due to the fact that the breakage of link 1-2, which connects the node with largest demand to the source node, in all networks (a), (b), (c), and (d) causes, respectively, 6.67, 10, 21.67, and 24.16 L/s water loss. This is while Tanyimboh and Templeman (1993) function gives the entropy value of network (d) more than network (c), and Hosseini and Emamjomeh (2014) modified function gives the entropy value of network (b) more than network (a). Therefore, neither Tanyimboh and Templeman (1993) nor Hosseini and Emamjomeh (2014) function can fully take into account the effect of connectivity order of the demand nodes to the source node in the entropy value of the network. A way for resolving this deficiency has been introduced in the following section.

3. Incorporating the effects of mechanical characteristics of the network links in the entropy function

As it was concluded in the previous section, even with all modifications, the entropy function presented by Tanyimboh and Templeman (1993) cannot consider the difference between various flow directions in calculating the entropy value realistically. Besides, although network reliability is significantly affected by both mechanical (including geometry of the pipe and its strength of material and roughness of the pipe wall) as well as hydraulic parameters, Tanyimboh and Templeman (1993) function fails to take into account the effects of mechanical specifications in entropy calculations. This is while the length of each link in a network is an effective parameter not only in the amount of probability of failure in that link, but also in the amount of the head loss. In the present study, to take into account the effect of mechanical characteristics of links along with their hydraulic properties, dissipated power in the network has been used. For this purpose, a new weighting factor $P_n^{''}$ based on the value of the dissipated power calculated in each link is defined for each node of the network, as follows:

$$P_n^{''} = \frac{T_n}{\sum_{i=1}^{nl} P_{wi}} \tag{8}$$

where, similar to the function proposed by Tanyimboh and Templeman (1993), T_n is the total outflow at node n, $\sum_{i=1}^{nl} P_{wi}$ is the total dissipated power by the water distribution network, and n_l is the total number of the links in the network. The dissipated power by link i, P_{wi}, can be calculated as:

$$P_{wi} = \rho g h_i Q_i \tag{9}$$

where ρ is water density, g is the gravity acceleration, h_i is the head loss for link i, and Q_i is the flow rate of link i. In this study, the link friction head loss is computed using the Hazen-Williams equation:

$$h_i = \frac{10.6 L_i}{D_i^{4.865} C_i^{1.85}} Q_i^{1.85} = K_i Q_i^{1.85} \tag{10}$$

where L_i is the length of the link i (m), D_i is the diameter of link i (m), C_i is the roughness coefficient of link i, and K_i is the resistance coefficient of link i (s/m^2). Based on equations (9) and (10) the dissipated power by link i can be calculated as:

$$P_{wi} = \rho g K_i Q_i^{2.85} \tag{11}$$

Having the values of P_{wi}, obtained by equation (11) the values of $P_n^{''}$ are calculated by Eq. (8), and are used instead of P_n in Eq. (1) which results in:

$$S = S_0 + \sum_{n=1}^{N} P_n^{''} S_n \tag{12}$$

for calculation of the network entropy, while the rest of calculations are the same as before. The network entropy values for different flow directions shown in Fig. 1 are presented in Table 1.

Table 1: Entropy values for three different flow directions in Fig. 1, using Tanyimboh and Templeman (1993) function *(S)*, the modified entropy function suggested by Hosseini and Emamjomeh (2014) *(S′)*, and the proposed entropy function in this study *(S″)*

Network	(a)	(b)	(c)	(d)
S	1.7155	1.4452	1.0513	1.1662
S′	0.9803	1.0201	0.9457	0.9332
S″	3.6629	2.4452	1.7119	1.4160

According to Table 1, the entropy value calculated by the suggested entropy function is in agreement with expectation. To calculate the value of dissipated power, the length of the peripheral links in the network as well as the diameter and roughness coefficient of all links were assumed to be 890 m, 400 mm, and 130, respectively. As an example of entropy calculations by the suggested function, which is based on the dissipated power, case (a) of the network shown in Fig. 1 is discussed here. The amounts of dissipated power in this network due to either of its links are given in Table 2.

Now, by using the total dissipated power of 14.0501 W of the network, as shown in Table 2, the network entropy value is calculated by using the suggested function as:

$$\begin{aligned} S_a^{''} = &-\frac{30}{14.0501}\left[\frac{6.67}{30}\ln(\frac{6.67}{30}) + \frac{14.17}{30}\ln(\frac{14.17}{30}) + \frac{9.16}{30}\ln(\frac{9.16}{30})\right] \\ &-\frac{14.17}{14.0501}\left[\frac{5}{14.17}\ln(\frac{5}{14.17}) + \frac{9.17}{14.17}\ln(\frac{9.17}{14.17})\right] \\ &-\frac{18.33}{14.0501}\left[\frac{5}{18.33}\ln(\frac{5}{18.33}) + \frac{13.33}{18.33}\ln(\frac{13.33}{18.33})\right] = 3.6629 \end{aligned}$$

To see the how the effect of length is incorporated in the network, it can be seen in Fig. 1-(a), as a sample, that both links 1-4 and 3-4 carry a portion of the water demanded in node 4, and also a portion of water demanded in node 2. These two links have almost the same flow rate, and therefore their breakage causes the same amount of water loss, but they have different lengths and different amounts of dissipated power as 2.1591W and 1.5315W, respectively.

Table 2: Dissipated power in different links of network (a)

Link	1-2	1-3	3-4	2-4	1-4	Sum
Dissipated power (Watt)	0.6182	5.2937	1.5315	4.4476	2.1591	14.0501

Obviously, link 1-4 has a higher probability of failure (assuming other conditions to be the same) than link 3-4 since it is longer. On this basis, link 1-4, should have a greater contribution in the network reliability, and therefore its entropy value, compared to link 3-4. In fact, this length effect is incorporated indirectly in the suggested entropy function through the dissipated power, appearing in the denominator of the fraction in Eq. (8), in which the incorporation of longer link is more than the shorter one. This is while both of Tanyimboh and Templeman (1993) entropy function and Hosseini and Emamjomeh (2014) entropy function fail to take into account this length effect.

4. Incorporating the amount and location of leakage in the entropy function

In preliminary studies, two fully-operational and non-operational modes of the links are considered as damage states in seismic performance evaluation of lifeline systems (Moghtaderizadeh, 1981, 1983). For example, in case of seismic evaluation of water supply systems, a given link with no damage is considered to be in its fully-operational mode; and in contrast, when the link is in breakage state, it is considered to be in its non-operational mode. In later studies, the two-state networks were generalized into multi-state networks (Ramirez-Marquez et al., 2006, Ming et al., 2007, Lisnianski, 2007), which is more appropriate for the network links exposed to earthquake hazard. In these models, a member can be considered in three performance states, namely, 100%, 50%, and 0%. As the number of performance states increases, the model tends to show a more realistic behavior. In fact, the real damage state of a link has a continuous nature between zero (non-operational) and one (fully-operational). From another point of view, seismic damage to water pipeline can be classified into water leakage and breakage. As leakage can be due to slight to extensive pipe damage, it cannot be classified into either states of fully-operational or non-operational.

In some previous studies, serviceability evaluation in water distribution network has been carried out with due consideration to leakage effect. Javanbarg et al. (2006) presented a method for modeling water leakage and pipe breakage. They mentioned that damaged pipeline can be modeled considering an orifice in the pipe wall or joint, which allows water to be discharged into the surrounding soil. They have explained that the leakage discharge for each pipe can be determined by the orifice equation. Water leakage modeling was performed via EPANET Software by using emitters which are pressure-dependent flow devices in the same way as the orifice. Similar to the pipe leakage, the emitter system can be used for the breakage modeling in which the emitter is considered to be located at the start node of the damaged pipe. In a case study, the method was applied to Osaka City water supply system, and serviceability of the network to ten hospitals was determined not only for analyzing the present system but also for considering two types of renovation plans. The results revealed that the flow analysis may lead to a more realistic method for evaluating the seismic vulnerability of water supply systems.

In another article, Javanbarg et al. (2007) presented a comprehensive redundancy model for water supply systems under earthquake hazards based on the basic concepts in the information theory. More specifically, they aimed to present a quantified measure of redundancy in water supply networks considering both breakage and leakage states of damage within the seismically damaged systems. In order to calculate the entropy and redundancy values in the water distribution network under earthquake hazards, they used the information entropy in a noisy channel/system. The earthquake environments were simulated as a noisy system of information, based on which they considered a pipeline network under a seismic risk similar to the one in a noisy system in the information theory. The total entropy of node j under seismic risk, $H_j'^{s}$, was expressed as follows:

$$H_j'^{s} = H_j' - L_j' \tag{13}$$

where H_j' and L_j' are total entropy and total entropy reduction at node j. They utilized an empirical equation to estimate the value of water loss in each leakage. After considering the value of leakage in pipes using empirical relations, network hydraulic analysis was performed using EPANET Software. Afterwards, the entropy of the damaged network was calculated using the obtained results from hydraulic analysis. In a case study, they applied their method to Kobe city water supply network.

With due consideration to the aforementioned cases, it could be concluded that the leakage effect has not been considered directly in entropy function in any of the previous studies. In other words, the entropy function was not modified in such a way to be suitable for calculating the network entropy considering possible cases of leakage in pipes. Not only the amount of leakage is of importance in the network performance and reliability, but also the leakage location has its own effect. In fact, when leakage occurs in a pipe two portions with different lengths and flow rates are created in that pipe, and as Eq. (10) shows the amount of dissipated power is a function of both length and flow rate in links of the network, and therefore it will not be the same for a network before and after leakage occurrence. In order to incorporate the amount and location of leakage in the network's links a modification is suggested here for calculation of P''_n, to be used in Eq. (12) for entropy calculation, is calculated as follows:

$$P_n'' = \frac{T_n'}{T_{Pw} + \Delta T_{Pw}} \tag{14}$$

where T_n' is the total outflow at node n after leakage, and ΔT_{Pw} is the difference between the dissipated power before and after leakage in the network, which is calculated as follows:

$$\Delta T_{Pw} = T_{Pw} - T_{Pw}' \tag{15}$$

where T_{Pw} and T'_{Pw} are the total dissipated power in the network before and after leakage, respectively. The value of T'_{Pw} is calculated as follows:

$$T_{Pw}' = \sum_{i=1}^{nl} P_{wi}' \tag{16}$$

where P'_{wi}, which is the dissipated power in the link in which the leakage has occurred, is calculated by:

$$P_{wi}' = \rho g k_i q_i^{2.85} + \rho g k_i' q_i'^{2.85} \tag{17}$$

where q_i and q_i' are respectively the flow rates in the two portions of the link with leakage, before and after the leakage location. In addition, k_i and k_i' are resistance coefficients for each link before and after the leakage location, which are obtained as follow:

$$k_i = \frac{10.6\, y_i}{D_i^{4.865} C_i^{1.85}} \tag{18}$$

$$k_i' = \frac{10.6(L_i - y_i)}{D_i^{4.865} C_i^{1.85}} \tag{19}$$

where L_i is the total length of the link, and y_i is the distance between the beginning of the link and the leakage location. In other words, y_i is the length of the pipe portion before the leakage location, and $(L_i - y_i)$ is the length of the pipe portion after the leakage location. To calculate the network entropy by Eq. (12), with consideration of the suggested modification, the outflow entropy at each node of the network, S_n, is now calculated by:

$$S_n = -\sum_{nj \in ND_n}^{N} P_{nj}' \ln P_{nj}' \tag{20}$$

as a modified version of Eq. (5), where instead of P_{nj} values, which relate to the network nodes before leakage, P'_{nj} values, which relates to the network nodes after leakage, given by the following equation

$$P_{nj}' = \frac{q_{nj}'}{T_n'} \tag{21}$$

are used, in which q'_{nj} is the flow from node n to node j after leakage occurrence. In the following section of the paper application of the proposed entropy function for various types of the distribution networks are presented.

5. Application of the proposed entropy functions in parallel, series, and loop networks

5.1. Parallel networks

In order to investigate the application of the proposed entropy function in parallel networks, two completely parallel networks with 2 and 3 links were considered as shown in Fig. 2.

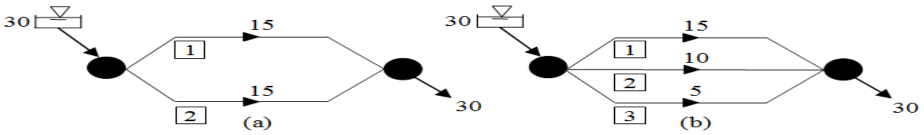


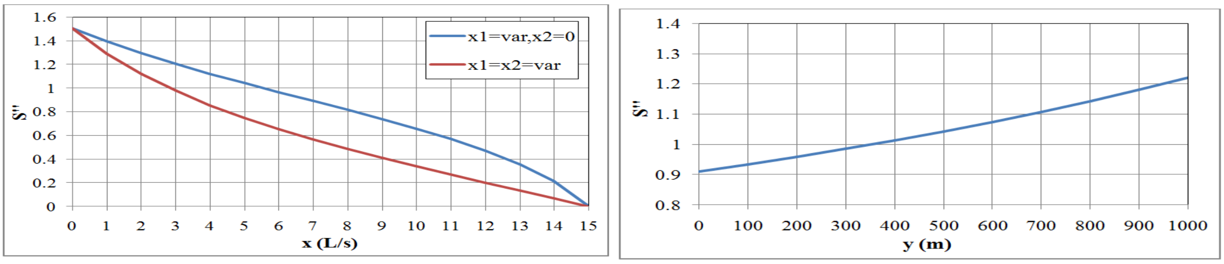
Fig. 2: Two Parallel networks with two and three links

In both networks the network inflow rate, the length, diameter, and roughness coefficient of the links were assumed to be as 30 L/s, 1000 m, 400 mm, and 130, respectively. The entropy value was calculated for the two-link network by assuming the same flow in its two links, resulting in the maximum entropy in the network. Assuming x_i as the value of leakage in link i and y_i as the distance from the beginning of the link to the leakage location, the entropy variations versus different leakage values and locations in the network were calculated as shown in Figs. 3 and 4.

It can be seen in Fig. 3-(a) that leakage causes reduction of the entropy value, as expected, and that this reduction is more when leakage occurs in both links of the network simultaneously. Also Fig. 3-(b) shows that the closer the leakage location is to the demand node, the higher the network entropy would be. To the best of the author's knowledge, all previous studies have failed to take this important factor into account.

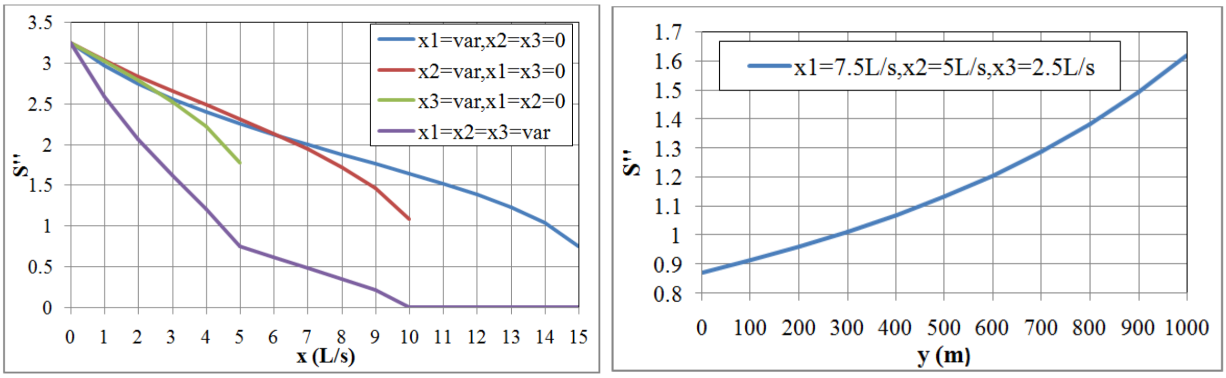
The three-link network shown in Fig. 2 has different flow rates in its links. The entropy value of this network was calculated once assuming various leakage amounts only in one link at its middle point, and once more assuming the same leakage amount at the middle point of all three links simultaneously. Another case was also considered as simultaneous leakage of half of the initial flow rate of each link, occurring at various locations along links, assuming the same y_i value in all three links. The results related to the first two cases are shown in Fig. 4-(a) and those related to the third case are shown in Fig. 4-(b).

Fig. 4-(a) shows the entropy variation of a three-link parallel network in 4 combinations of flow rate in the network's links.



(a) (b)

Fig. 3: Entropy variations in the two-link parallel network versus a) leakage amount assuming the leakage location at the middle point of the link(s), and b) leakage location assuming a fixed leakage amount of 5 L/s in one link of the network



(a) (b)

Fig. 4: Entropy variations in the three-link parallel network versus a) leakage amount assuming the leakage location at the middle point of the link(s), and b) leakage location assuming a fixed leakage amount in each link of the network

In the first three combinations, the leakage occurs in the middle of each link, and the value of leakage varies between zero and the whole flow rate of the link. In the fourth combination, the leakage occurs simultaneously in the middle of all three links, and the amount of leakage varies between zero and the whole flow rate of each link. It is observed that in all combinations, as the leakage increases, the value of network entropy decreases. By using Fig. 4-a, the sensitivity of each link to its corresponding possible leakage amount can be examined based on the amount of decrease it causes in the network entropy value. For example: when 3≤x≤5, link 3 is the most important link because in this leakage range, the value of network entropy is mostly reduced by leakage in link 3 rather than other two links. In the fourth combination, the same amount of leakage has been assumed in all three links simultaneously. In this combination when 0≤x≤5, the entropy value is much less than when the leakage occurs in one link, as expected. The two slope changes in the curve corresponding to this combination is due to the fact that actually x=5 and x=10 respectively means the complete breakage of link 3 and link 2. In case of x≥10 the value of network entropy would be zero since there is only one link from the source nodes to the demand node.

Fig. 4-(b) shows the entropy variations in a three-link parallel network for assumed values of leakage equal to half the flow rate of each link in different locations along the link. Similar to the two-link parallel network, the closer is the leakage location to the demand node the higher is the network entropy value. This can be due to the fact that shorter length of the link portion after the leakage location results in less dissipated power in the network.

5.2. Series networks

In order to investigate the variation of the proposed entropy function in series networks, a network with one supply node and two demand nodes has been considered. These nodes are connected serially as shown in Fig. 5.

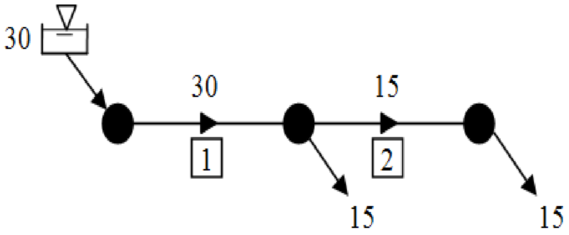
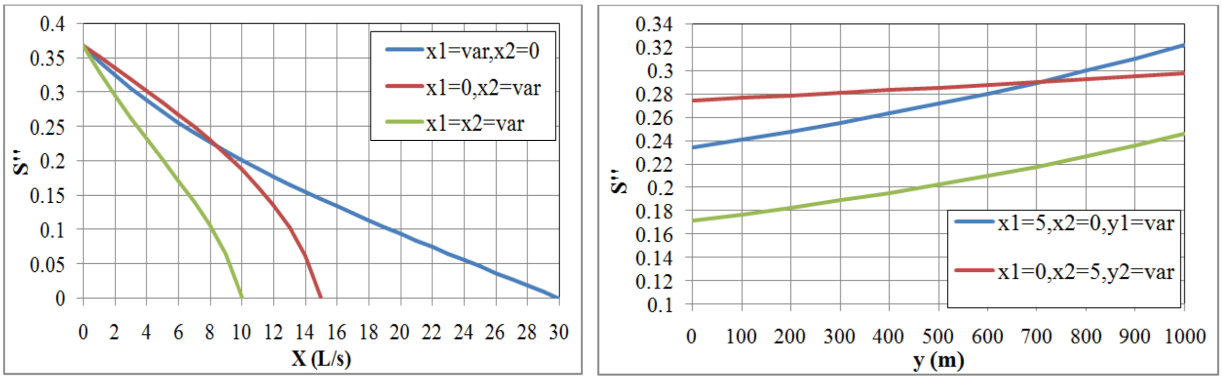


Fig. 5: The sample series network with two connected links

In this network, the amount of network inflow, the length, diameter, and roughness coefficient of each link, and the amount of demand in each node are considered to be 30 L/s, 1000m, 400 mm,130, and 15 L/s, respectively. Assuming *xi* as the amount of leakage in link *i* and y_i as the distance from the beginning of the link to the leakage location in link *i*, the entropy variations versus different leakage amounts and locations in the series network, shown in Fig. 5, were calculated and plotted as shown in Fig. 6.



(a) (b)

Fig. 6: Entropy variations in a series network versus a) leakage amount assuming the leakage location at the middle point of the link(s), and b) leakage location assuming a fixed leakage amount in each link of the network

Fig. 6-(a) shows entropy variations in a series network in 3 flow rate combinations. In the first and second combinations, leakage occurs in the middle of each link, and the leakage amount varies between zero and the whole flow rate of the link. Evidently, an increase in leakage amount in each link leads to a decrease in the entropy value in such a way that the entropy value becomes zero for x=30 L/s in the first link, i.e. when no water reaches the demand nodes. Also, when x=15 L/s, i.e. when no water reaches the second demand node, the entropy value becomes zero.

In the third combination, the amount of leakage in the middle of both links increases simultaneously. In this combination, when x1=x2=10 L/s, no water reaches the second demand node, and the entropy value becomes zero. In other words, it is unlikely that leakages more than10 L/s occurs in the two links simultaneously. When there is 10 L/s leakage in link 1, the value of flow transferred to the first demand node will be 20 L/s, 10 L/s out of which is consumed in the first demand node, and 10 L/s enters the second link. Since the amount of leakage in link 2 is also 10 L/s, no water can reach the second demand node. In all leakage combinations, the consumed water in the first demand node and the entered water to the second link are proportional to the water allocated in the first demand node and the link before leakage occurrence. In other words, half of the water reached to the first demand node is consumed in this node, and the other half enters the second link. By using Fig.6, the sensitivity of the network to possible leakages in each link is examined. For example, when the leakage happens in one link and 0≤x≤9, the link 1 is considered as the more important link due to the fact that the value of network entropy in this range is less than when the leakage occurs in link 2. However, when 9≤x≤15, the link 2 is the more important link due to the fact that the value of network entropy in this range is less than when the leakage occurs in link 1.

Fig.6-(b) shows network entropy variations based on a fixed leakage amount in different locations of the series network in 3 combinations. In the first combination, x1=5 L/s in different location of link 1 while there is not any leakage in link 2. In the second combination, x2=5 L/s in different locations of link 2 while there is no leakage in link 1. In the third combination, 5 L/s leakage occurs simultaneously in various locations in both links at the same distance from the beginning node. Hence, it could be concluded that the closer is the leakage location to the demand node; the higher is the entropy value.

5.3. Loop networks

In order to examine the behavior of the proposed entropy function in loop networks, the sample network, shown in Fig. 7, with one source node and 3 demand nodes was considered.

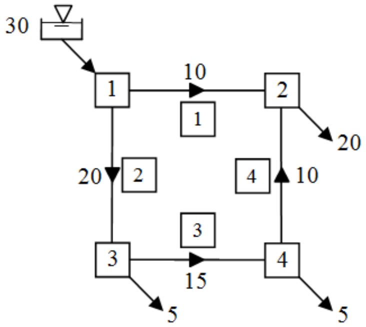


Fig. 7: The sample loop network with one source node and 3 demand nodes (Ang and Jowitt, 2007)

This network was first used by Ang and Jowitt (2003) for examining Tanyimboh and Templeman (1993) entropy function, for which the flow rates have been allocated to the links in such a way that result in the maximum value of the network entropy. The length, diameter, and roughness coefficient of all links are 890 m, 400 mm, and 130, respectively. Assuming x_i as the value of leakage in link *i*, the entropy variations versus different leakage amounts in the 500 m from the beginning of links could be calculated as shown in Figs. 8-10.

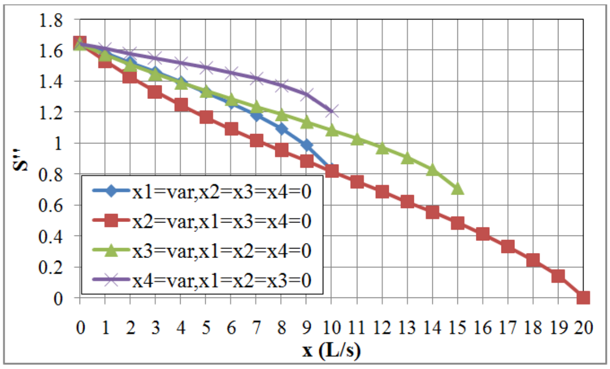


Fig. 8: Entropy variations of the loop network versus different leakage amount in each link

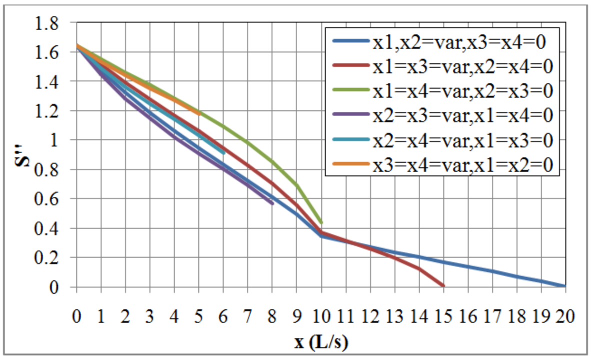


Fig. 9: Entropy variations of the loop network for leakage in 2 links with the same amount

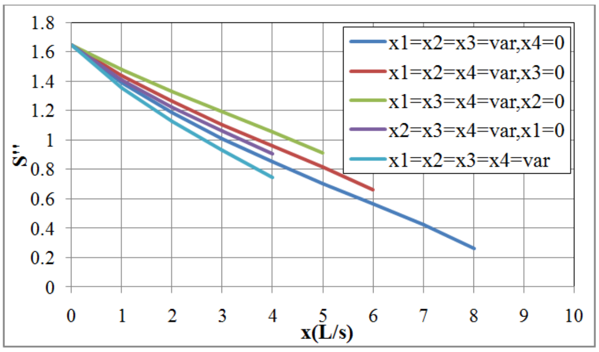


Fig. 10: Entropy variations in the loop network for leakage in 3 and 4 links with the same amount

Fig. 8 shows entropy variations in different leakage states in the loop network when the leakage occurs in just one of the links, and the leakage amount varies between zero and the flow rate of that link. Based on this diagram, the most important link for the state in which leakage may occur only in one link of the network could be identified. According to Fig. 8, link 2 is the most important one. This result is compatible with the expectation, as with due consideration to Fig. 7, it could be observed that link 2 has the highest flow rate in the network. Fig. 9 shows the entropy variation of the loop network in different states of simultaneous leakage in two links of the network with the same amount. Based on these diagrams, the pair of links whose simultaneous leakage creates the worst situation could be identified. According to Fig. 9, the network entropy value is the least when leakage occurs simultaneously in links 2 and 3. This result is also compatible with the expectation, as with referring to Fig. 7, the sum of flow rates in links 2 and 3 is more than that of other link pairs. Fig. 10 shows the entropy variations of the loop network in different states of simultaneous leakage of three links with the same amount, and a state of simultaneous leakage of all four links with the same amount. Based on these diagrams, the three-link set whose simultaneous leakage creates the worst situation could be identified. This results is also compatible with the expectation, as with due consideration to Fig. 7, it could be observed that sum of flow rates in links 1, 2, and 3, which equals that of links 2, 3 and 4, is more than that of any other three-link set. Why the three-link set 1, 2, and 3 is more important that the three-link set 2, 3, and 4 is that in the first set link 1 with 10 L/s flow rate supplies half of the demand of node 2, which has the highest demand in the network, directly from the source node, but this is not the case for link 4 with the same flow rate of 10 L/s in the second set. In other words, the proposed entropy function successfully takes into account the connectivity order of demand nodes to the source node in entropy calculations.

6. Conclusions

Based on the concept of informational entropy, the present study aimed to evaluate the serviceability of water distribution networks in view of both mechanical and hydraulic characteristics of the network as well as the values and location of possible link leakages under different hazard scenarios. To this end, two modifications were made in Tanyimboh and Templeman (1993) entropy function as follow:

1. Taking into account both mechanical and hydraulic characteristics of the network in the entropy function based on the concept of dissipated power in the network, by using a new weighting factor for each demand node, defined as the total outflow at the node to the total dissipated power in the network, instead of the previous ratio which had been defined as total outflow at each node to the total supply or demand of the network
2. Considering the effect of both amounts and locations of leakage in the entropy function based on modifying the proposed weighting factor by defining it as the total outflow at each node considering the leakage, divided by the total dissipated power in the network before the leakage plus the difference between the dissipated power before and after the leakage (it should be noted that the rest of the parameters in the original entropy function were redefined with respect to the hydraulically balanced network after the leakage.)

The proposed modified entropy function represent very well the difference between various flow distributions states of the network in comparison with previous defined entropy function.

Using proposed modified entropy function for several water distribution networks, including parallel, series and loop, it was revealed that the proposed entropy function can calculate the entropy value more realistically considering both mechanical and hydraulic characteristics as well as possible leakages in different links.

Also it was revealed that the closer is the leakage location to the demand node, the higher is the entropy value. Therefore, the modified entropy function could be efficiently used to evaluate the serviceability of existing networks, identify the most important link in the network under different hazard scenarios, determine the priority order for repairing or replacing links, and choose the optimal plan for designing new networks.

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