Failure analysis of the rainwater axial pumps installed in a wastewater pumping station

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Abstract. A strategy of urban sewage centralized management is implemented in the most cities (e.g. Timisoara). All wastewater is collected and conveyed to a central location for treatment or disposal. In the urban area, the rainwater is embedded in the wastewater management. Seven rainwater pumps are installed in a wastewater treatment plant to protect it against flooding. This type of pumps is vertically installed in Timisoara’s wastewater treatment plant in order to pump the additional rainwater protecting it. Several catastrophic events have been occurred at the rainwater pumps tacking them out of service after a limited operation time. The fastening bolts of the blades are brittle broken due to the clog of the impeller with waste rag balls. The cumulated operation time is examined for each rainwater pump together with the catastrophic events identified in service. The mechanical properties of the waste fibres are experimentally determined with respect to its area in order to assess the clog/rag conditions corresponding to the clearance between the impeller blades and housing. Next, the inertial torque associated to the rotating parts of the rainwater pump is estimated to check the level when sudden locking occurs due to the impeller clogging. The maximum stress level of the fastening bolts is exceeded when the impeller is partially clogged or ragged. As a result, the root cause of the problem is associated with the ragging level of the impeller. A solution is proposed to avoid these problems.

1. Introduction

A strategy of the urban sewage centralized management is implemented in the most cities (e.g. Timisoara). All wastewater is collected and conveyed to a central location for treatment or disposal. The wastewater treatment plant (WTP) of Timisoara was rehabilitated during 2009 – 2011 and it was commissioned in March 2011. The Timisoara’s WTP was designed to provide services for 440000 inhabitants, figure 1. Today, more than 350000 inhabitants (97% from the total number of Timisoara’s inhabitants), are connected to the city’s sewerage system. The annual average volume of the wastewater treated in Timisoara’s WTP is more than 42.1 million m\(^3\). The maximum capacity of Timisoara’s WTP is 3 m\(^3\)/s.

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In the urban area, the rainwater is embedded in the wastewater management. Up to 10% of the annual average volume of the wastewater treated in Timisoara’s WTP is rainwater. The additional flow rate from the rainwater over the maximum processing capacity of Timisoara’s WTP is discharged in Bega River to protect the municipal station against flooding. Seven single stage rainwater pumps with the flow rate of 24.5 m³/s (3.5 m³/s on each pump) are installed, figure 1.

![Figure 1. Aerial view of the rainwater pumping section of the Timișoara’s WTP.](image1)

Each pump is vertically installed in a reinforced column lifting the rainwater to an open channel linked with Bega River, figure 1. The pump is always completely submerged in operation enabling to cool the electrical motor, figure 2a,b. The parameters of the axial rainwater pumps are given in table 1. The dimensionless parameters are computed according to IEC60193 [1]. Each pump is suspended on the lifting chain in the center of the discharge column, figure 2c. Also, the power and signal cables needed to operate submersible propeller pumps are positioned inside the discharge column, figure 2d.

![Figure 2. Rainwater pumps installed in Timisoara’s WTP: (a) general view; (b) detailed view of the pump installed in the discharge column; (c) photo of the pump; (d) the technical solution with lifting chain.](image2)
The propeller pump is specially designed for wastewater systems being equipped with shape of the backward curved impeller along to the diffuser blade in order to minimize the clogging/ragging. Extensive investigations of the performances delivered both forward and backward curved pump impeller blades in both pump and turbine modes operation has been performed by Singh and Nestmann [2 - 4]. This type of propeller pump is equipped with anti-clog device [5, 6]. The blade design sweeps debris away to a relief groove in the wear ring, figure 3. The flow forces the debris to move towards the stay vanes and its further leaving the pump housing.

| Tabel 1. Parameters of the rainwater pump computed according to IEC60193 [1]. |
|---------------------------------------------------------------|
| Rainwater pump parameters | Values     |
| Speed $n$ [rpm] | 595        |
| Power $P$ [kW] | 400        |
| Discharge $Q$ [m$^3$/s] | 3.5        |
| Pumping head $H$ [m] | 9.2        |
| Impeller diameter $D=2R$ [m] | 1.2        |
| Characteristic speed $n_q=nQ^{0.5}/H^{0.75}$ | 211        |
| Discharge coefficient $\phi=Q/(\pi\omega R^3)$ | 0.08278 |
| Head coefficient $\psi=(2gH)/(\omega R)^2$ | 0.12911 |
| Power coefficient $\lambda=2P/(\rho\pi\omega R^5)$ | 0.01356 |
| Dimensionless specific speed $\nu=\phi^{0.5}/\psi^{0.75}$ | 1.336     |

Figure 3. Propeller impeller of the rainwater pump installed in Timisoara’s WTP: (a) side view; (b) front view; (c) exploded view.

Several catastrophic events have been occurred at the rainwater pumps, tacking them out of service after limited operation time. Therefore, the paper presents the failure analysis of the rainwater propeller pumps installed in a municipal wastewater treatment station. The rainwater pump operation
2. Rainwater pumps operation history

The operation procedure of the rainwater pumps is following: (1) one rainwater pump is starting when the threshold water level of 2.5 m in the suction chamber is reached; (2) one more pump is switched on at each 0.5 m added to the water level in the suction chamber. The pump start procedure is performed in increasing order, while the pumps are turned off in reverse order as they were started as the water level decreases by 0.5 m. The water level in the suction chamber is detected using a pressure sensor; (3) the procedure selects as the first pump in the following rain the next pump considering cyclic permutations to achieve a uniform distribution of the operating hours. The time operation in hours for each rainwater pump from 2011 to 2017 is detailed. The blade impeller failures of the rainwater pumps are described in Section 3. In Section 4, the analyses of the fibre failure mechanism and its mechanical properties as well as the brittle broken of the fastening bolts of the impeller blades due to clog of the clearance between the blade and house casing with waste fibres are presented, respectively. The conclusions are summarized in last section.

Table 2. Time operation in hours for each rainwater pump from 2011 to 2017.

| Year | P1 | P2 | P3 | P4 | P5 | P6 | P7 | Total |
|------|----|----|----|----|----|----|----|-------|
| 2011 | 63 | 51 | 75 | 111| 15 | 10 | 0  | 325   |
| 2012 | 23 | 4  | 22 | 43 | 37 | 16 | 10 | 155   |
| 2013 | 17 | 16 | 30 | 31 | 61 | 32 | 18 | 205   |
| 2014 | 39 | 2  | 65 | 32 | 27 | 42 | 33 | 240   |
| 2015 | 28 | 22 | 43 | 16 | 49 | 62 | 36 | 256   |
| 2016 | 65 | 53 | 54 | 43 | 76 | 57 | 77 | 425   |
| 2017 | 31 | 28 | 28 | 23 | 19 | 9  | 31 | 169   |
| Total| 266| 176| 317| 299| 284| 228| 205| 1775  |

A view of cumulated operation time in hours during 2011 – 2017 on each month is given in figure 4b. One can observe that the cumulated time operation larger than the average value of 135 hours for all twelve months of year is yielded during five months of the year (from April to August). These five months correspond to spring and summer seasons when the shower rains have had high intensity. The intensity of the shower rains has increased during last decade in Timiș County. The weather forecast performed by Romanian National Weather Service for Timiș County predicts an increase of the shower rains intensity [7].

Clogging/ragging is a critical and highly undesirable operational problem in wastewater and rainwater pumping unit [8 - 11]. It is known that clogging/ragging reduces pump efficiency, causes pump tripping and significantly affects the lifecycle costs. Especially, the unplanned costs associated with problems and downtime, such as: pump failure, pump clogging/ragging, station flooding, emergency calls, sewer backups, overflows are difficult to be estimated [12].

A few pictures with clogging/ragging aspects of the rainwater pumps are selected in figure 5. One can observe in these figures that both stay vanes and suction elbow favour the accumulation of debris with fibrous components and clogs/rags the pump impeller raising the friction forces and of course increasing the power needed to rotate impeller. As a result, the driving motor draws excess current
resulting in excessive energy consumption than normal. In situ measurements performed by our group on several rainwater pumps have revealed the tripping phenomenon [13].

Figure 4. Operation time for all seven rainwater pumping units from 2011 to 2017: (a) cumulated time for each rainwater pump and (b) cumulated time during each month.

Figure 5. Wastewater debris with fibrous components accumulated on the rainwater pump parts: (a) the impeller blades and the pump housing; (b) the stay vanes and (c) the suction elbow.

3. Damage description of the rainwater pumps

The rainwater pumps are required to operate in challenging environments and a key part of any regulations should be to operate reliably as well as efficiently over their expected lifetime. The pumps considered in this study are designed to be able to pump solid materials suspended within the water. The ability to handle fibrous components in the wastewater was also taken into account. However, two rainwater pumps have had catastrophic failures that took them out of operation for several weeks, figure 6. Two catastrophic events have been occurred at P1 pump in October 2013 and March 2016, respectively. Two impeller blades were destroyed at the first event at P1 pump, while three blades were damaged during second time. Other catastrophic damage has been occurred at the P4 pump in August 2014 when one blade was failed. It can be seen that the number of destroyed impeller blades changes from one case to another.
In all those cases, both fastening bolts of one blade and several blades are brittle fractured due to rag of the impeller with fibrous components of the waste, figure 7. It may be worth pointed out that several cracks are identified on the trailing edges of the impeller blades while a few damages are detected on its leading edges, figure 8.

Figure 6. Catastrophic failure with missing blades of the rainwater pump impellers: (a) P1 on October 2013 – 2 blades, (b) P4 on August 2015 – 1 blade and (c) P1 on March 2016 – 3 blades.

Figure 7. Catastrophic failure of the rainwater pump impeller: (a) one blade is missing, (b) mechanical solution with two fastening bolts of the impeller blade on the hub and (c) the brittle facture surfaces of both fastening bolts.

Figure 8. Damage of the impeller blade: (a, b) cracks on the trailing edge and (c) damages on the leading edge.
4. Failure analysis of the rainwater pump impellers

The analyses of the fiber failure mechanism and its mechanical properties, as well as the brittle broken of the fastening bolts of the impeller blades due to rag of the clearance between the blade and house casing with waste fibers are presented, respectively.

Experimental investigations were done on the waste collected from the municipal wastewater system. The chemical composition and microscopic analysis of the waste material is performed. As a result, the waste composition is determined as follows: 17% dyes and amines, 16% fats and 67% fibres, [14]. The microscopic examinations performed on fibers in transversal direction, respectively in longitudinal direction indicate that the structure of a composite material consisting from fibers, fats and solid particles with different sizes [15]. Two microscopic snapshots in longitudinal and transversal directions of the waste debris are included in figure 9.

![Microscopic snapshots of the waste debris: (a) transversal and (b) longitudinal sections.](image)

The mechanical properties under tensile and shear loadings of the dry and wet fibres collected from rainwater pumps are extensively investigated by Galațanu et al. [14]. It has been observed that the tested specimens show different thicknesses and structures because they are formed as random strings during storm discharge. The average value for shear strength of the dry fibres is 16.55 MPa, while for wet fibres reach 55.13 MPa. The composite structure of the waste specimens (fibres, sand, and so on) plays an important role during the shear tests in order to define it strength. The average shear strength is 3.3 times higher for the wet fibres than the dry ones, figure 10.

It can be seen that the average shear strength is 2.9 times higher than the tensile strength for the dry fibres, figure 10. The difference between shear and tensile strengths is given by fact that in case of the tensile tests breakage is achieved progressively by tearing, the fibres being non-homogeneous in their length while in the case of shear tests all area of fibres is directly loaded.

It was determined a different behaviour of the dry and wet fibres under the tensile tests because the water acts like a plasticizer and it strongly modifies the mobility of the amorphous part of macromolecules and shifts, similar as temperature [16, 17]. The moisture drastically changes the properties of fibres. The results lead to the conclusion that wet fibres require a higher force for breaking both under tensile and shear loading.

A linear correlation between the breaking force and the fibres cross section area was obtained for tensile/shear loading [14]. These correlations are used to estimate the force required to break by stretching or shearing the fibres which rag the clearance between the impeller blades and the pump casing.
The energy conservation law is used to analytically estimate the dynamic torque of the rainwater pump. The suddenly stop of motion elements constitute an impact phenomenon, which assumes transformation of kinetic energy \(E_c\) of the rotating parts of the rainwater pump in the deformation energy of its parts \(U\). The energy transferred is given by equation (1) considering negligible energy losses:

\[
E_{c,\text{max}} = U_{\text{max}}
\]  

where \(E_c = \frac{1}{2} \omega^2 / 2\) is the kinetic energy corresponding to the entire rotating parts of the rainwater pump with \(J\) [kg m\(^2\)] is the moment of mechanical inertia and \(\omega\) [rad/s] is the angular velocity.

The kinetic energy is estimated taking into account the angular speed \(\omega\) of the rotating parts and the moment of mechanical inertia of the rotating assembly \(J\) with respect to the axis of the pump unit. The moment of mechanical inertia is determined using equation (2)

\[
J_i = \frac{(G_i R_i^2)}{2}
\]  

where \(R_i\) [m] is the radius of each component of the assembly and \(G_i\) [kg] represents their weight for each rotating part \(i\). In our case, the rotating parts are the following: impeller with four blades, hub, shaft and electrical rotor. The impeller blades and hub are manufactured by Bronze-Aluminum alloy with high corrosion resistance, good hot and cold malleability but a medium workability. The shear modulus \(\mu\), moment of mechanical inertia \(J\) and the kinetic energy \(E_c\) of the rotating parts associated to the rainwater pump are given in table 3.

**Table 3.** Shear modulus, moment of mechanical inertia and the kinetic energy of the rotating parts.

|            | Impeller | Shaft | Rotor |
|------------|----------|-------|-------|
| \(\mu\) [GPa] | 52.5     | 81    | 49    |
| \(J\) [kg·m\(^2\)] | 4.002    | 3.028 | 72.105 |
| \(E_c\) [kJ]  | 7.77     | 5.87  | 139.97 |

The angular velocity of \(\omega=62.31\) rad/s corresponds to the constant speed of \(n=595\) rpm at the rainwater pump shaft. As a result, the kinetic energy of the entire rotating assembly of the rainwater pump unit is 153.63 kJ. One can observe that the main contribution is delivered by electrical motor.

Deformation energy is given by the formula:

\[
U = \frac{1}{2} \int_0^L \frac{M_i^2}{G_i \nu_i} dx = \frac{1}{2} M_t^2 \cdot \frac{1}{k_i^p}
\]  

where \(M_i\) [Nm] is the moment of torsion, \(k_i^p\) is torsional stiffness coefficient of the assembly components, \(L\) [m] is the length, \(\mu_i\) [MPa] is the shear modulus and \(I_{p,i}\) [m\(^4\)] is the polar moment of inertia.
The moment of torsion \( M_t \) of the entire rotating assembly is determined using equation (5):

\[
M_t = \frac{1}{\int L \frac{d}{\Theta_l p_*}}
\]

The moment of torsion \( M_t \) of the entire rotating assembly is determined using equation (5):

\[
M_t = \omega \sqrt{\sum (f_i \cdot k_i)}
\]

Consequently, the moment of torsion is \( M_t=9392.96 \) kNm. The stress on the fastening bolts located between the hub and impeller blades is estimated considering a uniform loading on both bolts:

\[
\tau = \frac{2M_t}{NA_{fb}D_{med}}
\]

where \( N=2 \) is the number of the fastening bolts for each blade, \( A_{fb}=\pi D_{fb}^2/4 \) is the minimum cross section area of the fastening bolt located at the end of the screw with diameter of \( D_{fb}=22 \) mm and \( D_{med}=(D_1+D_2)/2=0.32375 \) m is the average diameter of fastening bolts arrangement with \( D_1=0.3135 \) m and \( D_2=0.334 \) m, respectively. The stress on each fastening bolt is estimated around of \( \tau=76362.13 \) MPa.

The fastening bolts are manufactured by stainless steel 316L A4 according to ASTM, respectively 1.4401 after EN with high corrosion resistance but low wear resistance. One can observe that the stress on each fastening bolt is several times larger than the shear strength of \( \tau_r=800 \) MPa if the entire rotating parts of the rainwater pump is suddenly locked. This observation leads to the conclusion that the partial ragging of the clearance area between the impeller blades and the pump casing causes breaking of the fastening bolts according to the investigations performed by Galaţianu et al. [18]. Conclusively, the maximum stress level of the fastening bolts is exceeded when the impeller is partially clogged. As a result, the root cause of the problem is associated with the ragging level of the propeller impeller.

5. Conclusions

The paper focuses on failure analysis of the rainwater propeller pumps installed in Timisoara’s municipal WTP. This type of pumps installed in WTP is presented. The catastrophic events occurred at rainwater pumps have taken them out of service after a limited operation time. The cumulated operational time in hours for each pump from 2011 to 2017 is detailed. The total operation time of all rainwater pumps from 2011 to 2017 is 1775 hours. The cumulate time in service associated to the pumps is varying from 176 hours for pump P2 to 317 hours for pump P3. A deviation of -31/+25% is obtained for minimum/maximum value with respect to average one of 244 hours for all seven pumps. As a result, the procedure to ensure a uniform time operation can be improved.

Next, the catastrophic failures occurred in service are listed. In all those cases, both fastening bolts of one or several blades are brittle fractured due to rag of the impeller with fibrous components of the waste. Therefore, the chemical composition and the microscopic analysis were done on the waste debris collected from the pumps. The waste composition was determined as follows: 17% dyes and amines, 16% fats and 67% fibres. Further, the microscopic examinations performed on fibres in transversal direction, respectively in longitudinal direction indicate the structure of a composite material consisting from fibres, sand, stones and fats. The mechanical properties under tensile and shear loadings of the dry and wet fibres collected from pumps was performed. As a result, the average value for shearing strength of the dry fibres is 16.55 MPa while for wet fibres of 55.13 MPa, respectively. It can be seen that the average shearing strength is 2.9 times higher than the tensile strength for the dry fibres. The specimens tested shows different thicknesses and structures because of them are formed as random strings during storm discharge.

The inertial torque associated to the rotating parts of the rainwater pump is analytically estimated to check the level when the sudden locking occurs due to the impeller rag. The moment of mechanical inertia and the kinetic energy of the rotating parts are estimated. Then, the maximum stress level of the fastening bolt is several times exceeded the shear strength threshold of the material when the impeller is suddenly locked. As a result, the root cause of the problem is associated with the ragging level of the impeller. In the future, different solution can be explored to reduce the maintenance cost and to extend the lifetime of the rainwater pumps. The Variable Speed Drives (VSD) on rainwater pumps is one solution to control reversals of direction in order to help free blocked impellers [19-21].
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