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## Original Research Article

# Comparative analysis of circular and three-lobe journal bearings using smart electrorheological and magnetorheological lubricants

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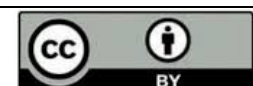
### ABSTRACT

A numerical investigation on steady state indices of the conventional circular and three-lobe journal bearings lubricated with smart electrorheological (ER) and magnetorheological (MR) fluids is presented in this study. The generalized Reynolds equation is solved by finite element method and the non-linear behavior of lubricant is represented by Bingham constitutive relation to take into account the field-dependent viscosity and yield stress. A comparative analysis is performed on the effects of bearing geometry and smart lubrication on pressure distribution, minimum film thickness and the viscous power loss. Results show that the hydrodynamic performance is much better when activating ER and MR fluids. In circular bearings, minimum film thickness is increased by 4.26% (ER) and 5.85% (MR) as compared with Newtonian lubrication and maximum enhancement in the three-lobe bearing with MR fluid is 6.67%. There is also a small increase in frictional power loss (ER +0.87% and MR +2.47%). Overall, MR lubrication coupled with multi-lobe geometry helps in making the greatest inroads into improved bearing performance.

## 1. Introduction

Three-lobe journal bearing is a non-circular bearing that features a 120 degree three-lobe profile in order to extend load capability, reduce friction and to provide a higher level of vibration stability in applications demanding high speeds such as turbomachinery, turbocharger, and aerospace applications. Their performance is strongly controlled by lobe aspect ratio, radial clearance and pressure distribution. Crosby and Chetti [1] showed that couple stress lubricants markedly increase the stability in comparison with Newtonian fluids. Kumar et al. [2-3] showed that the lobe configuration has a critical effect in stiffness and dynamic response under shear-thinning lubrication. Ren and Feng [4] reported the improved stability in water lubricated hybrid bearings by optimized clearance and pocket parameters. Narwat et al. [5-6] highlighted the additive benefits of providing transverse roughness in the turbulent flow regime on improving film thickness, stiffness capability and damping capability by non-Newtonian lubricants. Abass and Mahdi [7] found improved load capacity and lower friction due to the application of micro-ridges, while micropolar effects have also enhanced stability in lemon bore bearings [8]. CFD examinations by Mehrotra et al. [9] highlighted the effects of lubricant rheology to pressure and turbulence behavior and Singh et al. [10] confirmed that electrorheological lubricant significantly increases stiffness, damping and threshold speed, resulting in better dynamic stability. Surface texturing involves introducing micro- or nano-scale features such as grooves, dimples or cavities onto bearing surfaces to improve lubricant film behaviour, namely increasing load capability, reducing friction and increasing wear opposition. Costa and Hutchings [11] reviewed texturing methods, and key conclusions were that electrochemical texturing without a mask was the fastest and cheapest method as well as inkjet printing providing a

trade-off between cost and resolution. Cupillard [12] proved, using CFD, that suitable texture profile and topography reduce the viscous friction and increase the pressure production, particularly for low-mid eccentricity ratio. Extensive study [11-22] ascertains the advantages of surface texturing in fluid film bearings. Numerical inquiries [13-14] revealed that optimized transverse roughness and half-section micro-dimples near leading edge will enhance the load capability, stiffness, and reduce the frictional losses in hybrid thrust pad bearings. Brizmer and Kligerman [15] provided ideal laser surface texturing parameters for the load capability of journal bearings. Studies on magnetohydrodynamic hybrid thrust bearings [16-17] showed that the enhanced load and stiffness characteristics are achieved with micro-grooves combined with electrical performing lubricants. Lu et al. [18] published results of improved friction performance using phyllotaxis-based dimple arrangements. Narwat et al. [19-20] showed that partial surface texturing using electrorheological lubricants has significantly improved the stiffness, damping, and threshold speed in multi-lobe journal bearing. Torabi and Alidousti [21] demonstrated the reducing effect of textured surfaces under elastohydrodynamic condition which are in good concordance with numerical and experimental result. Singh et al. [22] further optimized the micro-groove parameters in hybrid thrust bearing by utilizing the FEA through JFO condition and ANN based technique (ANN-GA-TLBO), showed great performance improvement. Smart lubricants such as magnetorheological (MR) fluids, electrorheological (ER) fluids, nanostructured lubricants and self-healing lubricants have responsive and versatile properties to external stimuli to ensure real-time control of lubrication performance. Ongoing study [23] focuses on improving their productivity, stability and response speed



towards automotive and industrial systems. Urreta et al. [24] studied hydrodynamic journal bearings lubricated with ferro- and MR fluids by verifying viscosity modulation concepts with theoretical and experimental analyses. Numerical examinations [25-26] revealed that magnetic fields dramatically add to load capability and damping in the case of hydrostatic thrust bearings in the case of low Hartmann numbers and optimized recess and restrictor configurations. Bompos and Nikolakopoulos [27] used CFD and FEM to analyze MR journal bearings with different magnetic domain strength and L/D ratio with different values of eccentricity to show the impact on flow and friction. Laukiavich et al. [28] have compared ferro- and MR fluids for active control of hydrodynamic bearings for different running conditions. Sharma and Kumar [29] showed that the activation by couple stress additives combined with a transverse magnetic domain makes a significant improvement in load capability, stiffness and damping in hydrostatic thrust bearings. Lampaert et al. [30] suggested a hybrid journal bearing (Utilizing both hydrostatic and hydrodynamic effects) bearing with MR fluid and localized magnetic fields to maintain the hydrodynamic and hydrostatic regimes. More recently, there have been some studies [31-32] for the optimization of textured two-lobed journal bearings with MR lubricants using Fuzzy-MOGA optimization of bearing elements which indicated a significant improvement in stiffness and threshold speed resulting in a significant improvement in dynamic stability. The use of electrorheological (ER) lubricants in smart mechanical devices, such as fluid film dampers, automotive clutches, hydrodynamic journal bearings, thrust bearings, and valves, is now growing [33] because of its ability to precisely regulate the viscosity of a lubricant using an applied electric domain. Finite element examinations, by using Bingham fluid model [34], have shown that ER lubricants greatly enhance load capability, stiffness, and damping in hydrostatic thrust bearing, performing depend much on pocket geometry and compensating components. Jang and Tichy [35], based on their research, said that although load capability changes are almost unaltered at low eccentricities, higher electric fields improve stiffness and load support in journal bearings. Further studies [36-37] emphasised the benefits of using hybrid thrust bearings united in ER lubricants and surface texturing. Experimental and theoretical work [38] confirmed that ER fluids enable the adaptive control of vibrations and increase dynamic stability at high speeds. CFD analyses by Peng and Zhu [39] indicated that the load carrying capability is enhanced by electric fields especially at high eccentricity ratios and low speeds with little impact on attitude

angle. Christidi-Loumpasefski et al. [40] showed improved dynamic coefficients and vibration suppression in ER lubricated journal bearings using finite element modelling. More recently optimized textured hybrid thrust bearings with ER lubricants and artificial intelligence-based approaches (ANN-GA-TLBO) [22] demonstrated good improvements in steady state and dynamic performances due to the optimal micro-groove design. The proposed work shows comparative analysis of circular and three-lobed journal bearings operation with both electrorheological (ER) and magnetorheological (MR) lubricants in electric and magnetic (external) field. Unlike previous research which analyzed the lobe geometry and smart lubricants separately this research combines these two aspects and analyzes their connected effect on pressure distribution, minimum film thickness and film frictional power loss. By carrying out integrated assessment for both ER and MR instances, the research provides lubricant-specific benchmarking of performance, as well as geometry-specific benchmarking of performance, providing pragmatic guidelines for the design of next-generation flexible and adjustable smart journal bearing system.

## 2. Mathematical formulation

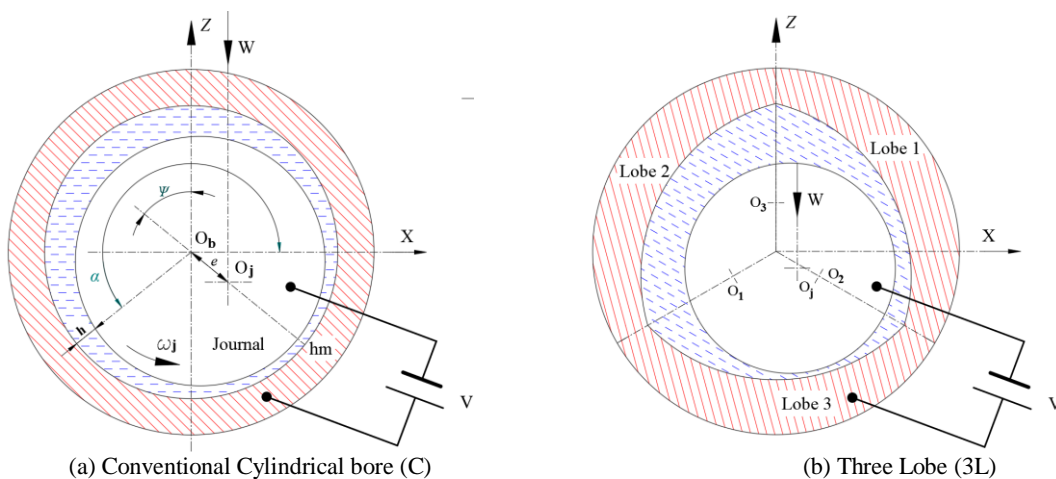
The geometric profiles of conventional cylindrical bore and three-lobe journal bearings are presented in Figures 1 (a–b). The lubricant flow within the clearance space between the journal and the bearing is described by the generalized dimensionless Reynolds equation [2], as presented in Equation (1). The effect of viscosity is incorporated through the cross-viscosity integral functions ( $\bar{F}_0, \bar{F}_1, \& \bar{F}_2$ ).

$$\frac{\partial}{\partial x} \left( \bar{h}^3 \bar{F}_2 \frac{\partial \bar{p}}{\partial x} \right) + \frac{\partial}{\partial y} \left( \bar{h}^3 \bar{F}_2 \frac{\partial \bar{p}}{\partial y} \right) = \Lambda \frac{\partial}{\partial x} \left[ \left( 1 - \frac{\bar{F}_1}{\bar{F}_0} \right) \bar{h} \right] + \frac{\partial \bar{h}}{\partial t} \quad (1)$$

The film thickness expressions for circular and three-lobe journal bearing profiles can be reformulated as follows [2]:

$$\bar{h} = \frac{1}{\delta} - (\bar{x}_j - \bar{x}_1^i) \cos \alpha - (\bar{z}_j - \bar{z}_1^i) \sin \alpha \quad (2)$$

here  $[\bar{x}_j, \bar{z}_j]$ , and  $[\bar{x}_1^i, \bar{z}_1^i]$  denote the dimensionless coordinate of the journal center and the  $i$ th lobe center, respectively. For a conventional circular bearing, the offset factor ( $\delta$ ) approaches unity, and the lobe center coordinates coincide with the origin.



**Figure 1:** Operational arrangement for journal bearing system operating with smart (ER) fluid.

According to the Bingham constitutive law [35], the relationship among apparent viscosity ( $\bar{\mu}$ ), zero-field viscosity ( $\bar{\mu}_0$ ), threshold yielding stress ( $\bar{\tau}_0$ ) and strain-rate ( $\bar{\gamma}$ ) can be defined as:

$$\bar{\mu} = 1 + \frac{2\bar{\tau}_0}{\pi\bar{\gamma}} \tan^{-1} \left( \frac{\bar{\gamma}}{\bar{\gamma}_0} \right) \quad (3)$$

Carlson [41] proposed an empirical relationship, based on the Dave model, to describe the yielding stress of the magnetorheological fluid (MRF-122EG). In this formulation, the yielding stress dependent on the iron particle volumetric concentration ( $\varphi_i$ ) the applied magnetic field strength ( $B_i$ ), and base oil coefficient ( $k_i$ ).

$$\tau_y = k_i * 271700 * \varphi_i^{1.5239} * \tanh(6.63 * 10^{-06} * B_i) \quad (5)$$

The Reynolds Boundary Condition (RBC) is applied in solving Equation (1) to predict nodal fluid film pressures. The Galerkin finite element method is employed to minimize the Reynolds equation residue across the fluid flow, wherein the shape function are used as weighting function in the error minimization process.

$$\iint_{\Omega_e} (N_j * R_{es}) d\bar{x}d\bar{y} = 0 \quad (6)$$

Following the assembly of the elemental matrices into the global system matrix, the simplified version of Eq. (6) is expressed as follows:

$$[\bar{F}_{ij}] \{ \bar{p} \} = [\bar{Q}_i] + \Lambda [\bar{H}_i] + \bar{x}_j [\bar{S}\bar{Q}_x] + \bar{z}_j [\bar{S}\bar{Q}_z] \quad (7)$$

The steady-state indices are evaluated by neglecting the squeeze motion of the shaft center. The variations in the shaft/rotor center coordinates are subsequently expressed in matrix-form and solved using the multivariate Newton Raphson technique.

$$[\Delta \bar{x}_j] = - \begin{bmatrix} \frac{\partial \bar{F}_x}{\partial \bar{x}_j} & \frac{\partial \bar{F}_x}{\partial \bar{z}_j} \\ \frac{\partial \bar{F}_z}{\partial \bar{x}_j} & \frac{\partial \bar{F}_z}{\partial \bar{z}_j} \end{bmatrix}^{-1} \begin{bmatrix} \bar{F}_x \\ \bar{F}_z - \bar{W} \end{bmatrix} \quad (8)$$

The journal center coordinates are updated iteratively until convergence is achieved. The new equilibrium position of the journal center is obtained once the specified convergence criterion—based on the eccentricity ratio is satisfied, as given below:

$$\sqrt{\frac{(\Delta \bar{x}_j)_i^2 + (\Delta \bar{z}_j)_i^2}{(\bar{x}_j)_i^2 + (\bar{z}_j)_i^2}} < 10^{-5} \quad (9)$$

The steady-state performance indices of the journal bearings are computed as:

$$\text{Net film reaction force: } \bar{F} = \sqrt{\bar{F}_x^2 + \bar{F}_z^2} \quad (10)$$

$$\bar{F}_x = \int_{-1}^{+1} \int_0^{2\pi} \bar{p} \text{Cos}\alpha d\bar{x}d\bar{y} \quad (11)$$

$$\bar{F}_z = \int_{-1}^{+1} \int_0^{2\pi} \bar{p} \text{Sin}\alpha d\bar{x}d\bar{y} \quad (12)$$

Frictional power loss (Laminar):

$$\bar{P}_f = \int_0^{2\pi} \int_{-1}^1 \left( \frac{h}{2} \left( 1 - \frac{\bar{F}_1}{\bar{F}_0} \right) \frac{\partial \bar{p}}{\partial \bar{x}} + \frac{\bar{\mu}\Lambda}{h} \right) d\bar{y}d\bar{x}. \quad (13)$$

Minimum Fluid Film Thickness: The minimum film thickness is simulated using the following relation once the equilibrium journal center coordinates are established.

$$\bar{h}_{min} = \text{Min}(\bar{h})_{1*n}, \quad (14)$$

where  $n$  represents the number of nodes in the flow domain.

### 3. Results and discussions

The finite element method (FEM) is used to numerically simulate the performance of traditional cylindrical bore and three-lobe journal bearing lubricated using an ER and MR fluids. In order to account for the non-linear rheological behavior of the fluid, the Bingham constitutive model is used. The rheological properties of the ER and MR fluid are borrowed from the literature. The geometric and operating parameters for the journal bearing analysis are taken from the published reference studies [1-2, 24, 28, 35 39, 41, 42]. The accuracy and convergence of scheme is evaluated by monitoring the ratio of eccentricity and convergence is considered to be achieved when the variation of the ratio of eccentricity between consecutive iterations is accurate and true till the 6th significant digit i.e., An organized and systematic mesh of 51×31 nodes (circumferential x axial) is adopted to ensure grid independent and reproducible numerical results. may be associated with differences in the way the numerical results implementation, mesh discretization, and convergence criteria accepted in the respective analyses. The developed model has been verified by the theoretical and experimental inquiries reported by Urreta et al. [29]. In their study, the authors investigated the load supporting carrying capability of circular bearings due to the application of magnetorheological lubrication for various values of eccentricity ratios. he experimental analysis was carried out by applying the magnetorheological fluid MRF-122-2ED which is supplied by LORD Corporation [29]. A comparison between the load carrying capability as a function of eccentricity ratio between the experimentation-based results in [29] and the predictions of the current mathematical model. This comparison indicated that there is good agreement with the maximum deviation of 10.8% from the experimental data. A comparative evaluation of the open surface fluid pressures contour for standard cylindrical bore and three-lobe journal bearings with three lubrication conditions, Newtonian lubricant (NL; I =0), electrorheological lubricant (ER; V =800V) and magnetorheological lubricant (MR; I =4 A), is presented in Figure 2. The application of an outside electric or magnetic area energises the ER/MR lubricants, and this results in a noticeable enhancement in the maximum film pressure values and over all pressure gradients. This augmentation is connected to the formation and agglomeration of chain-like ER/MR microstructures in the smart fluids which significantly increases the obvious viscosity. Increased viscosity increases

the hydrodynamic pressure area so that load-carrying capacity is increased and the pressure distribution in the bearing clearance is more favourable. Moreover, in the three-lobe bearing configuration the zenith film pressure is further increased compared to the used in traditional circular geometry. The elevation in the maximum pressure is more

visible with MR lubrication than ER lubrication for both the cylindrical and three-lobe bore bearings, forging the conjoined effect of multi-lobe geometrical configuration and MR fluid activation in strengthening the hydrodynamic pressure generation.

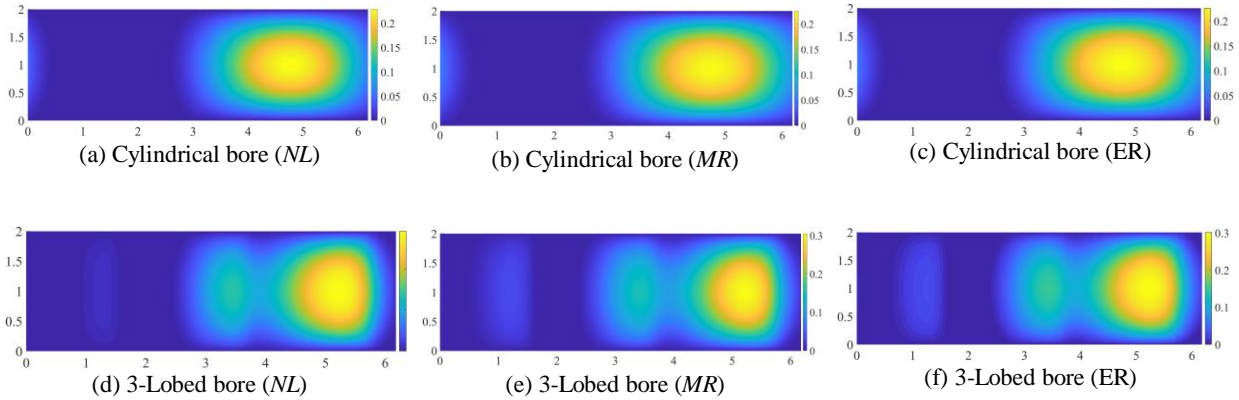


Figure 2: 2D Pressure Profile contours for cylindrical and three-lobe bearings.

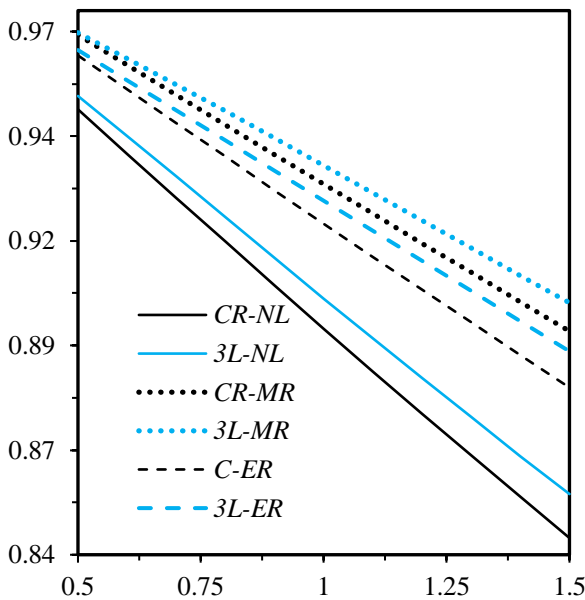


Figure 3: Min. Film Thickness Vs Load

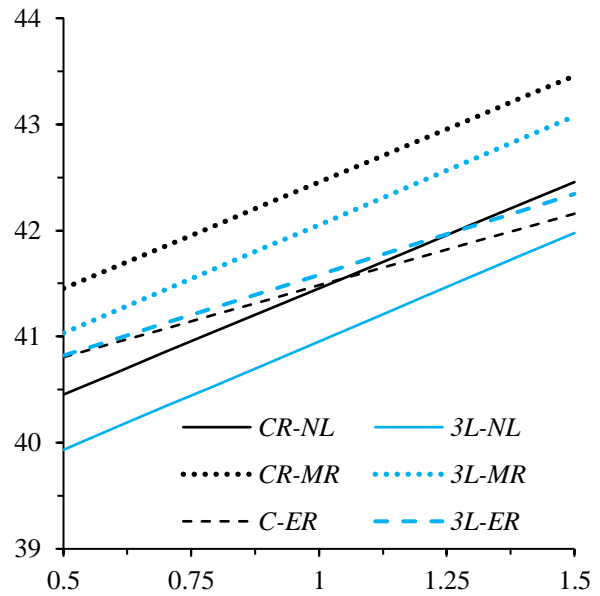


Figure 4: Viscous Loss Vs Load

Since fluid film pressure profile and its gradients are the controlling factors in the steady-state indices of bearing system, such advancements are very important to the overall bearing behaviour. Figure 3 shows the variational trends for of minimum film thickness ( $\bar{h}_{min}$ ) with applied load for the cylindrical and three-lobe bearings. As expected the minimum film thickness reduces with increasing load due to increasing journal eccentricity at higher running conditions. However, use of ER and MR lubricants results in a perceptible and discernible improvement of minimum film thickness for both configurations. This improvement is related to the microstructural alignment induced in the field by ER/MR fluids, which increases the apparent viscosity and allows the formation of a thicker supporting lubricant film, as compared to Newtonian lubrication. The MR lubricant has a somewhat higher influence than the ER lubricant. For circular bearings, an improvement of +4.26% (ER) and +5.85% (MR) in minimum film thickness is found when compared with the Newtonian case. The three-lobe bearing coupled with MR

lubrication gives the utmost and preminent improvement with +6.67% enhancement in the minimum film thickness compared to the baseline cylindrical bore bearing working with a Newtonian fluid. Figure 4 gives an elaborate and exhaustive evaluation of the effects of bearing geometry and smart lubricants (ER/MR) on viscous power loss ( $\bar{P}_f$ ). A consistently increasing trend in the viscous power loss is observed with increasing applied load. The introduction of ER and MR lubricants results in a small and minor increase in viscous power loss with maximum increase of +0.87% and +2.47% respectively in case of cylindrical bore bearing. This increase is related to the high level of enhanced viscosity created by microstructure formation under activating field, which leads to an increase of shear stresses existing in the lubricant film. Additionally, the three-lobe bearing has more frictional power loss than the circular configuration. This behavior can be explained by the increase in wetted surface area and more complicated and intricate flow attributes associated with the multi-lobe geometry, which cause increased viscous

dissipation. The additional lobes pose some additional shear zone, thus increasing the frictional forces and the accompanying power loss.

#### 4. Conclusions

In this numerical investigation on the steady-state indices of cylindrical bore and three-lobed journal bearing operating with smart electrorheological (ER) and magnetorheological (MR) fluids using a finite element method based on the Reynolds equation and Bingham model. The electric or magnetic activated lubricants ER and MR increase the obvious viscosity as a result of the generation of a chain-like micro structure. This leads to higher apex fluid film stresses, load carrying capability, and an increase in minimum film thickness, when compared to conventional Newtonian lubrication. For circular, three lobed configurations MR lubrication always produces higher maximum film pressure and minimum film thickness. The improvement is remarkable in three lobe bearing in particular, indicating the better field responsive phenomena of MR fluid under the same running conditions. The three-lobe configuration increases the generation of hydrodynamic pressure and even more so in combination with smart lubricants, enhancing the minimum film thickness. However, this geometric revision further causes the additional viscous power loss because of added interaction of the surfaces and enhancement in viscous inside the lubricant film.

#### Authors' contributions

The author reviewed and approved the final version of the manuscript for publication.

#### Conflicts of interest

The author declares no conflict of interest.

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#### Data availability

No new data were created.

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