An efficient data processing scheme for the analysis of in-situ stresses in concrete structures

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Abstract

In the present paper, the application of the centre hole technique to concrete structures is examined and an efficient scheme developed for the determination of the in-situ stresses. An effective data processing procedure for the complex strain relaxation data is proposed. The variability of concrete as a material makes it necessary to improve on previous techniques, also the high degree of redundancy in the test data must be dealt with. In the proposed procedure, a so-called *'surface stress'* is defined which allows for the elimination of the influence of any surface effect which inevitably exists in concrete structures. In order to minimise the error in the derivation of in-situ stresses, an iterative method is established to deal with the redundant data recorded during the tests. A detailed example is given for the application of the present method to strain relaxation data from site measurements. The results show improved accuracy and efficiency of data analysis, and the capability for practical use.

1. Introduction

The Centre hole technique is the most accurate and cost effective method for in-situ stress determination. It has been successfully used in metal structures during the past four decades.[1] Recently this technique was further developed by introducing incremental hole drilling to determine stress variation with hole depth.[2,3,4] Schajer's integral method of data analysis has a well founded theoretical background and may easily be implemented.

In order to apply the centre hole technique to concrete structures, an instrument coring method [5-8] was developed in 1986 by Strainstall

Engineering Services Ltd. as a complimentary approach to their wide range of in-situ stress measurement techniques. The variability of concrete as a material required modification of the standard centre hole technique, in which a high degree of redundancy was employed both in strain relaxation measurements and modulus determination. These improvements provided reliable information to minimise the test error mainly caused by the difference between the characteristics of steel and concrete material. However, it transpired that the derived stress state which varied with hole depth was not stable when Schajer's integral method[3] was directly applied to concrete structures without any modifications. Furthermore, large deviations would occur in the determined stress fields when different combinations of the redundant strain relaxation data were used.

In the present paper, the application of the incremental hole drilling technique to concrete structures is examined by developing an efficient data processing procedure. *Surface stress* is defined to eliminate the influences of the surface effects[6] which inevitably exists in concrete structures. In order to minimise the error in the derivation of in-situ stresses, an iterative scheme is established to deal with the redundant data recorded during the tests. A detailed example is given for the application of the present method to strain relaxation data from site measurements. The results show improved accuracy and efficiency of data analysis, and the capability for practical use.

2. Coring Technique in Concrete Structures

As a composite, concrete is a mixture of several materials. The manufacturing stresses between the matrix and the aggregate are balanced. From a global point of view, the in-situ stresses equal the dead load stresses as the balanced manufacturing stresses can be neglected. However, this balance may be lost when a hole is drilled through the matrix and aggregate and local stresses are often produced. Furthermore, micro-cracking may be initiated during stress relief, particularly when those caused by shrinkage are relieved. These make it difficult to obtain an accurate strain relaxation measurement. In order to eliminate these local stress effects and to increase the reliability of the measurements, a modified coring technique is introduced to enhance the centre hole technique. The hole diameter is increased to an appropriate value, usually between 35-100mm. The type, size and number of strain gauges, and the hole/gauge layout are also re-arranged.

In the current method, a standard 78mm diameter core is drilled incrementally using a diamond core drilling. The hole/gauge geometry comprises a rosette of eight strain gauges surrounding the core with one additional gauge placed centrally on the core as shown in Figure 1. Vibrating Wire (VW) strain gauges with two inch length are used to eliminate the effect of local stresses.

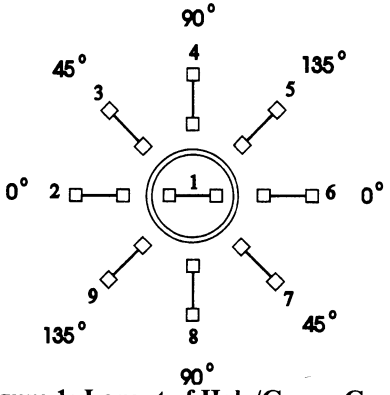


Figure 1: Layout of Hole/Gauge Geometry.

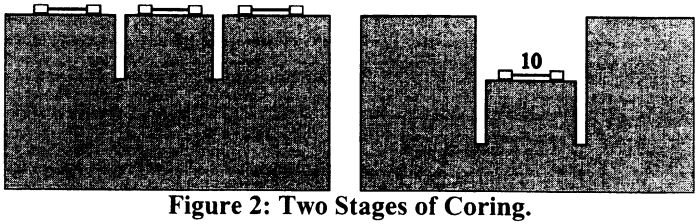


Figure 2: Two Stages of Coring.

The core is drilled incrementally and the coring procedure is divided into two stages as shown in Figure 2. At the first stage, a core is drilled to 50mm in 5mm increments. Strain readings of the nine gauges are recorded before and after each step. Then the 50mm length core is removed from the structure and the bottom of the hole is flattened. The strain relief from the material deeper than 50mm has no effect on the surface gauges. Thus, only a single gauge is installed centrally on the bottom of the hole along the direction of maximum stress determined from the results of the first stage. Thereafter, a second core is made to depth of 50mm in 10mm increments. The readings of this subsurface gauge are also recorded step by step.

Ten sets of strain readings from these ten gauges are produced, which provide a high degree of redundancy in strain relaxation measurements since any three sets of data in different directions are sufficient to determine the in-situ stress state.

3. In-situ Stresses and Strain Relaxation Relationship

The basic idea of centre hole technique is to derive in-situ stresses from strain redistribution while a relatively small hole is drilled in the stress field. The key feature of this technique is therefore the determination of the relationship between in-situ stresses and surface strain relaxation measurements.

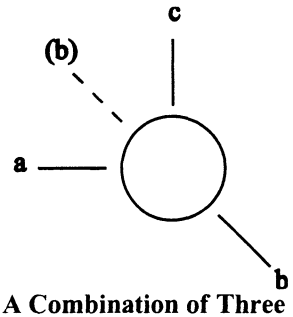


Figure 3: A Combination of Three Strain Gauges.

As mentioned before, three sets of independent strain measurements are sufficient to determine the in-situ stress field which consists of three components, i.e. σ_a, σ_c, τ_{ac} once the three gauges shown in Figure 3 is used as a possible combination. During the derivation, linear transformations are made for simplification to both stress field and strain relaxation[3],

$$P = (\sigma_a + \sigma_c)/2 \qquad Q = (\sigma_a - \sigma_c)/2 \qquad T = \tau_{ac} \tag{1}$$

$$p = (\varepsilon_a + \varepsilon_c)/2 \qquad q = (\varepsilon_a - \varepsilon_c)/2 \qquad t = (\varepsilon_a + \varepsilon_c - 2\varepsilon_b)/2 \tag{2}$$

where, P, Q, T are transformed stress matrices and p, q, t are transformed strain relaxation matrices. With the above transformation, the stress-strain relationship could be simply expressed as,

$$AP = Ep/(1+\nu) \qquad BQ = Eq \qquad BT = Et \tag{3}$$

where, E and ν are Young's modulus and Poisson's ratio, respectively. The calibration matrices A and B, which can be obtained from Finite Element (FE) analyses, are functions of the hole/gauge geometry, but independent or weakly dependent on material properties. For a given hole/gauge geometry, the element a_{ij}, b_{ij} in the lower triangular matrices A and B have the value of,

$$a_{ij} = \frac{E}{1+\nu}\frac{\varepsilon_{aij} + \varepsilon_{cij}}{\sigma_j} \qquad b_{ij} = E\frac{\varepsilon_{aij} - \varepsilon_{cij}}{\sigma_j} \qquad (1 \le j \le i) \tag{4}$$

where, ε_{aij} and ε_{cij} are the surface strain relaxation due to the relief of σ_j, which is the stress on *j-th* layer while the hole is at *i-th* layer. Figure 4 shows the FE model used in the evaluations of A and B.

After the evaluations of A and B, the in-situ stress field can be derived according to the following procedure,

(1) Linearly transform the measured strain relaxation ε_a, ε_b and ε_c into p, q, t using Equation (2).

(2) Calculate P, Q and T from Equation (3).

(3) Transform P, Q, T into σ_a, σ_b and τ_{ac} from Equation (1) as,

$$\sigma_a = P + Q \qquad \sigma_b = P - Q \qquad \tau_{ac} = T \tag{5}$$

(4) Evaluate the principle stresses from Equation (5) as,

$$\sigma_{max,min} = P \pm \sqrt{Q^2 + T^2} \qquad \beta = 0.5\tan^{-1}(T/Q) \qquad (6)$$

where, σ_{max} and σ_{min} are the maximum and minimum principal stresses, respectively, and β denotes the direction of principal stress.

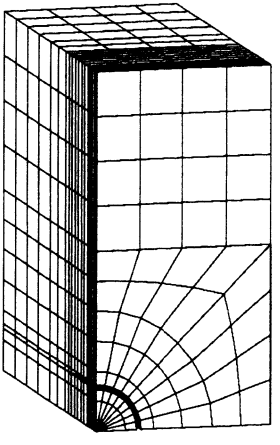


Figure 4: FE Mesh.

4. Data Processing

The surface effects[6] which inevitably exist in concrete structures may cause in-situ stresses to vary with depth. In order to eliminate these effects, it is necessary to introduce the concepts of Schajer's integral method[3], which cope with stress variations with hole depth. Theoretically, this method could be used on any kind of material. However, as mentioned in the introduction, modifications are required during its application to concrete structures.

The in-situ stress states are relatively lower in concrete structures than those in metal ones, which makes the derived stresses sensitive to the measured strain data. The initiations of micro-cracking in the vicinity of the gauges may cause further errors in the strain measurements. In order to minimise the errors, an iterative scheme is established in the present paper to deal with the redundant strain relaxation measurements.

4.1 Sensitivity Analysis

In the present paper, the sensitivity is defined as the error of the determined stress field induced by the error in the strain relaxation measurements. As shown in Figure 5, sensitivity analysis revealed that, one micro-strain error of strain relaxation would induce an error of 1.5N/mm^2 in the derived stress state, or a 15% error for a practical concrete structure which generally has a stress state below 10N/mm^2. In order to improve the accuracy, the curves of strain relaxation variation with hole depth are usually smoothed using such technique as the Least Squares method. In the present paper, an iterative method is established to deal with the redundant strain relaxation data, during which, the strain curves are smoothed simultaneously during the in-situ stress derivation.

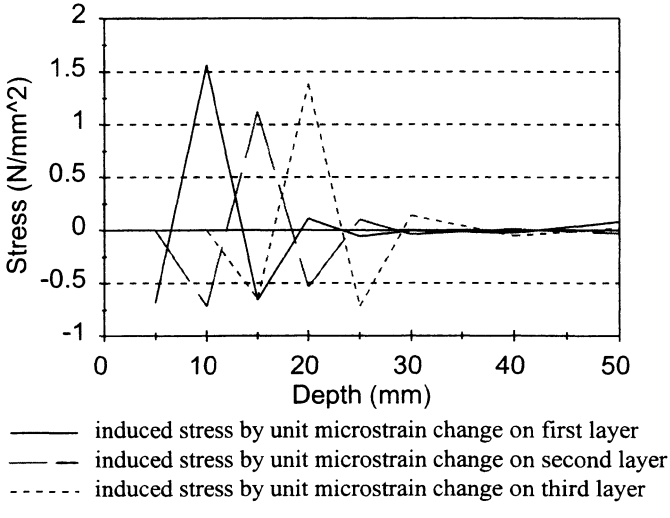


Figure 5: Induced Stress Caused by Unit Microstrain Change on Strain Measurement.

4.2 Iterative Method

Using the data recorded at each drilling step, the strain variations with the hole depth can be obtained. From these curves, unreasonable results are eliminated by the operator. As shown in Figure 1, the pairs of gauges in opposite positions should theoretically have the same readings. Therefore, four independent records can be identified from the eight radial gauges. In the present paper, the average value of each pair are used, i.e.

$$\varepsilon_0 = (\varepsilon_2 + \varepsilon_6)/2, \varepsilon_{45} = (\varepsilon_3 + \varepsilon_7)/2, \varepsilon_{90} = (\varepsilon_4 + \varepsilon_8)/2, \varepsilon_{135} = (\varepsilon_5 + \varepsilon_9)/2 \quad (7)$$

where, the subscript denotes the gauges shown in Figure 1. These four data sets, together with those two from the core gauges cause a high degree of redundancy in the strain relaxation measurements. Generally, the combination of ε_0, ε_{45} and ε_{90} is employed to evaluate the stress state.

As practical concrete structures are designed to be subject to compressive loads, the stress state is usually constant with depth. However, the derived stresses generally vary with the hole depth due to surface effects which inevitably exist in concrete structures. Careful observations of in-situ test records[6] revealed that, surface effects usually existed over the depth up to 15mm. Therefore, the total stress field σ_{total} is defined in the present paper as,

$$\sigma_{total} = \sigma_{av} + \sigma_{su} \tag{8}$$

where, σ_{av} is assumed to be a constant stress and could be calculated by averaging the derived stresses over the range of depth of 15mm to 40mm. σ_{su} is the surface stress, which results from the surface effects and varies within the depth up to 15mm.

After the evaluation of σ_{av}, a strain field due to the average stress σ_{av} could be easily calculated. The difference between the calculated strains and the strain relaxation measurements is taken to be the result of surface effects, and used to derive the surface stress σ_{su}. It is then a straightforward exercise to calculate the total stress σ_{total} from Equation (8). Its induced strain variations in the four pairs of radial gauges and the core and sub-core gauges can then be evaluated.

As the total stress field is derived from those of ε_0, ε_{45} and ε_{90}, its induced strain curves will usually be consistent with their corresponding test records. The induced strain curves in this case are used as a reference to review the measured strain curves. This can result in one gauge being favoured over another in a pair, or need to take the average of the pair, or more likely it may involve relatively small changes to the profile given. However, large deviations sometimes do exist in the first iterative step between the induced strain curves and the test records for the rest of the gauges. It can be proven theoretically that the deviation in ε_{135} results from τ_{ac}, while the deviation in the core gauge is produced by σ_a and σ_c. Further iterative steps are therefore conducted by making relatively small modifications to the corresponding stress components of σ_{av} or σ_{su} according to the deviation; until satisfied results of both strain and stress are obtained. The iterative procedure is also illustrated by a flow chart in Figure 6.

The above procedure does not involve the strain relaxation measurements from the sub-core gauge since this is only normal to determine the in-situ stresses using the first hole drilling stage in most cases. As mentioned before, the average stress is assumed to be a constant value when the depth is over 15mm. The stress state in the second stage is thus identical to its first stage value of σ_{av}. The data recorded by the sub-core gauge may also, therefore, be employed as a reference during the iterative process.

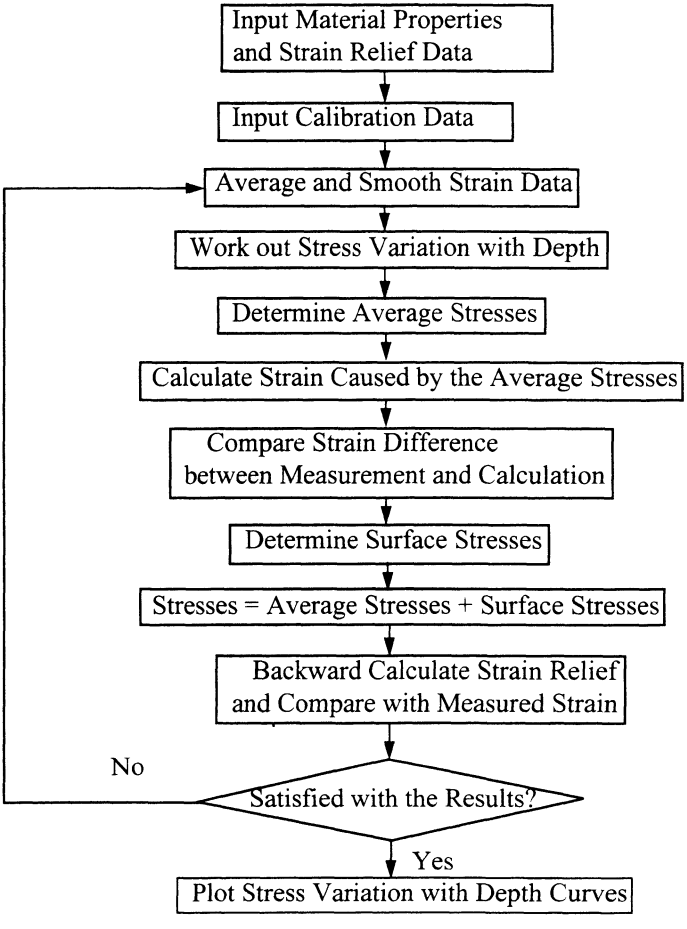


Figure 6: Flow Chart of Iterative Procedure.

5. Example

Strainstall Engineering Services Ltd. has carried out more than 200 in-situ stress determinations using the centre hole technique. Recently, measurements were conducted on the North Approach Viaducts of the Kingston Bridge, Glasgow, as part of a large programme of work for Scott Wilson and Kirkpatrick acting as consultants to Strathclyde Regional Council.[7] A total of 43 measurements were carried out on the approach viaducts with the stress state being predominantly uniaxial compression longitudinally. One of the measurements located at its mid-span is taken as an example in this paper.

The material properties from site measurements were Young's modulus E=33000 N/mm^2, Poisson's ratio ν=0.2. The ten sets of strain relaxation measurements from both radial and core/sub-core gauges recorded are shown in Figure 7. Four independent sets of strain change data are therefore calculated from Equation (7). The average strain change curves are also shown in Figure 7.

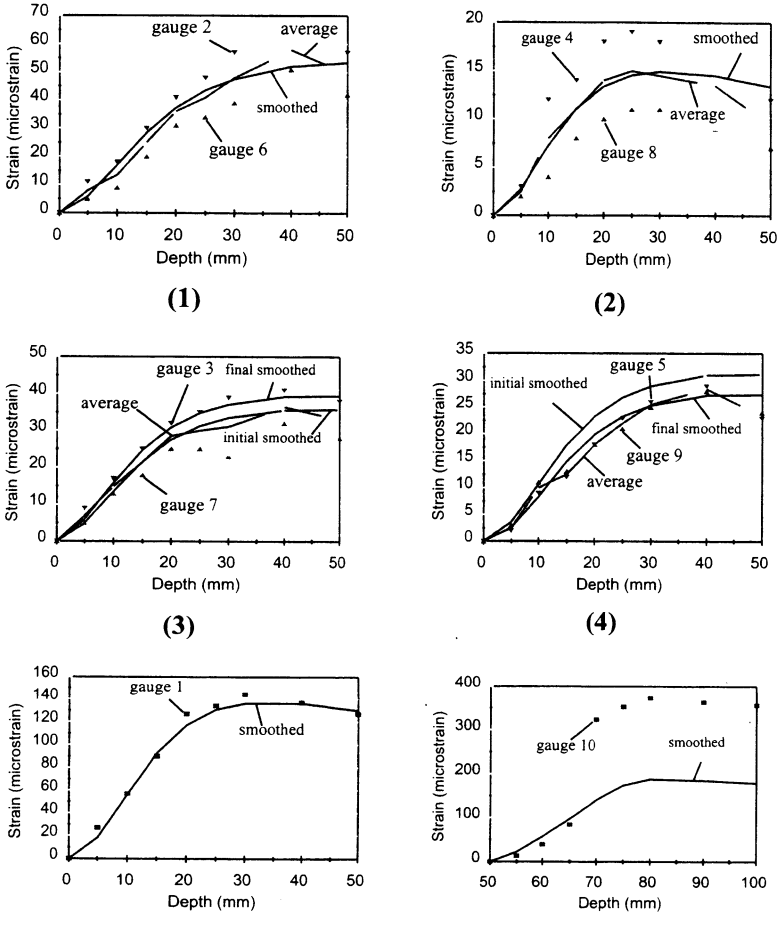


Figure 7: Strain Relaxation

7.1 Strain Change with Depth on 0° Direction
7.2 Strain Change with Depth on 45° Direction
7.3 Strain Change with Depth on 90° Direction
7.4 Strain Change with Depth on 135° Direction
7.5 Strain Change with Depth on core gauge
7.6 Strain Change with Depth on sub-core gauge

Figure 8 illustrates the values of σ_{total}, σ_{av} and σ_{su} evaluated from the strain change curves of ε_0, ε_{45} and ε_{90} according to the present procedure. The induced strain variations of σ_{total} in the four pairs of radial gauges and the core gauge are shown in Figure 7.

It is revealed in Figure 7 that, the calculated strain variation of ε_0, ε_{45} and ε_{90} are coincidence with those corresponding averages. Relatively large deviation is revealed for the curve of ε_{135}. However, the calculated and recorded strain curves on the core gauge agree with each other.

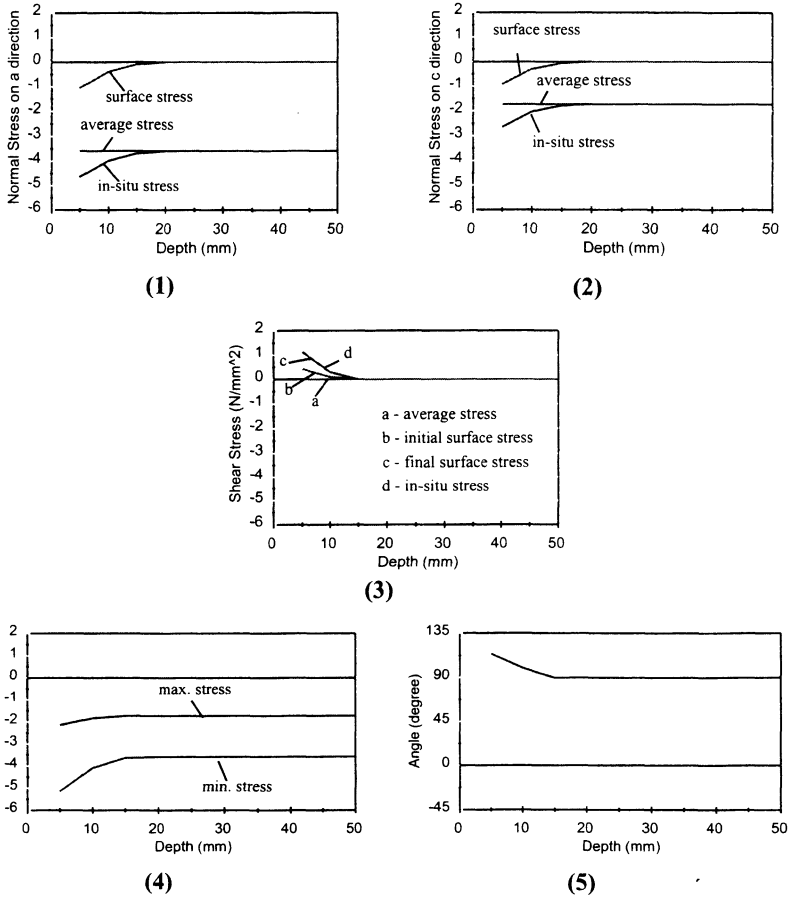


Figure 8: Stress Variation with Depth

8.1 Normal Stress σ_a Varies with Depth
8.2 Normal Stress σ_c Varies with Depth
8.3 Shear Stress τ_{ac} Varies with Depth
8.4 In-situ Principal Stresses Vary with Depth
8.5 Direction of Maximum Stress

As mentioned before, the deviation of the two strain curves in Figure 7.4 results from the shear stress component of τ_{ac}. Further iterations are therefore carried on by slightly modifying τ_{ac} until agreements for all strain change curves are achieved. In the present example, final results of the strain and in-situ stress fields are obtained after three iterative steps. These final results are shown in Figure 7 and Figure 8.

Since relatively small changes were only made for the stress component τ_{ac} during the iterations, the smoothed strain curves at the directions of 0° and 90° do not change (Figure 7.1 and Figure 7.2). However, it is shown in Figure 7.3 that after iteration the gauge 3 is favoured over gauge 7 by comparing the recorded stain relaxation measurements of these two gauges and the calculated strain curve. The final smoothed strain curve for the sub-core gauge is plotted in Figure 7.6, which shows an unreasonable deviation in the recorded strain relaxation measurements for which a modification is required.

6. Conclusions

In the present paper, the practical coring technique for concrete structures[5,6] is efficiently integrated with Schajer's integral method[3] by developing an effective iterative data processing procedure. With the definitions of average stress and surface stress, a stable in-situ stress field can be determined from redundant strain relaxation measurements. A detailed example is given for the application of the present method to those strain relaxation data from in-situ measurement, which yields improved accuracy and efficiency. The whole process is automatically carried out on a PC by spreadsheet computer program which is available for practical use.

In the present paper, the defined surface stress is assumed to be the result of surface effects such as shrinkage, carbonation etc. Further studies on its inducement should be made either experimentally or theoretically, which is beyond the scope of the present paper.

Acknowledgements

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