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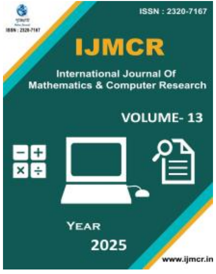

On Common Fixed-Point Results for Expansive Type Mappings in Cone Rectangular Metric Spaces

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ABSTRACT

In this paper, we establish common fixed-point theorems for a class of self-mappings satisfying expansive-type conditions within the framework of cone rectangular metric spaces. These generalized metric spaces incorporate a cone structure in a real Banach space, allowing for a partial ordering and broader applicability beyond traditional metric settings. We provide sufficient conditions under which such mappings admit a unique common fixed point. The presented results extend and refine several known fixed-point theorems. Additionally, examples are included to demonstrate the applicability and effectiveness of the theoretical findings in generalized metric and nonlinear analysis contexts.

MATHEMATICS SUBJECT CLASSIFICATION (2020): Primary: 54H25; Secondary: 54E50, 47H10.

KEYWORDS: Normal cone, cone rectangular metric spaces, coincidence point, common fixed point, expansive type mappings.

1. INTRODUCTION

Fixed point theorems concern maps f of a set X into itself that, under certain conditions, admit a fixed point, that is ,a point x ϵ X such that f(x) = x. The knowledge of the existence of fixed points has relevant applications in many branches of analysis and topology. By a contraction on a metric space (X, d), we understand a mapping $T : X \rightarrow X$ satisfying for all $x, y \in X$: $d(Tx, Ty) \leq kd(x, y)$, where k is a real in $[0,1)$.

Branciari [4] introduced a class of generalized (rectangular) metric spaces by replacing the triangular inequality of metric spaces with a similar one which involves four or more points instead of three points. The author also improved Banach Contraction Principle in such spaces. Recently many authors Cho, S.H.[6], Chaira K, et.al. [5] proved the existence and uniqueness of a fixed point for different types of mappings.

Azam A [2], introduced the concept of cone rectangular metric space by replacing the triangular inequality in the definition of cone metric space with a rectangular inequality and proved the Banach contraction principle on these spaces.

2. PRELIMINARIES

Definition 2.1. [2] Let X be a non-empty set. The mapping $d_E : X \times X$ said to be cone rectangle metric space if it satisfies:
(1) $\alpha < d(x,y)$, for all $x, y \in X$ with $x \neq y$ and $d(x,y) = \alpha$ iff $x = y$;
(2) $d(x,y) = d(y,x), for\ all\ x, y \in X$;
(3) $d_E(x,y) \leq d_E(x,w) + d_E(w,z) + d_E(z,y)$;
for all $x, y \in X$ and for all distinct points $u, v \in X - \{x, y\}$.

Definition 2.2. [10] Let P be a subset of a real Banach space $E\ and\ \alpha$ is the zero vector of $E. P$ is said to be a cone in E if it satisfies the following properties:
(i) P is non-empty, closed and $P \neq \alpha$
(ii) $x, y \in P$ implies a $\boldsymbol{x} + \boldsymbol{by} \in P$, where a and b are positive real numbers;
(iii) The intersection of P and $-P$ is $\{\alpha\}$

Definition 2.3. [10] A cone P is said to be a solid cone if an interior of P is a non-empty subset of E.

Definition 2.4. [10] A partial order relation $\le$ with respect to a solid cone $P \subseteq E$ is defined as $\boldsymbol{x} \le \boldsymbol{y}$ if $\boldsymbol{y} - \boldsymbol{x} \in P$, for x, y ∈ *E*.

Definition 2.5. [10] A cone *P* is called a normal cone if there is a number $k > 1$ such that for all **x**, **y** ∈ X, $\alpha \le x \le y$ implies that ||**x**|| ≤ k||**y**||.

Definition 2.6. [2] Let(X,d_E) be a cone rectangular metric space and *P* be a solid cone in *E:* Then the sequence $\{x_n\}$ is said to converge to x if $d_E(x_n,x) \to 0$ *as* $n \to \infty$

Definition 2.7 [2] Let (X,d_E) be a cone rectangular metric space and *P* be a solid cone in *E:* Then the sequence $\{x_n\}$ is said to be Cauchy if for all p > 0 we have $d_E(x_n, x_{n+p}) \to 0$ *as* $n \to \infty$

Throughout this paper, *P* is not necessarily a normal cone in *E;* the relation *x*≪*y.* stands for *y ,x* belongs to an interior of *P* and *R* denotes the set of all Real numbers.

3. MAIN RESULT

Theorem 3.1: Let (X,d_E) be a cone rectangular metric space. If the mappings P and Q : X→X satisfying the condition:

$$d_E(Px,Py) \ge \alpha_1 d_E(Qx,Qy) + \alpha_2 d_E(Px,Qx) + \alpha_3 d_E(Py,Qx) + \alpha_4 d_E(Py,Qy) \qquad (3.1.1)$$

for all x, y∈ X,where $\alpha_1, \alpha_2, \alpha_3, \alpha_4 \in R$ such that $\alpha_1 \ge 2$ *and* $0 < \alpha_2, \alpha_3, \alpha_4 < \frac{1}{2}$.

If Q(X)⊆P(X) and either of Q(X) or P(X) is a complete subspace of X, then Q and P have a unique coincidence point in X. Further, if Q and P are weakly compatible self -maps then they have a unique common fixed point in X.

Proof: let x_0 be an arbitrary point of X. Since Q(X) $\subseteq P(X)$ and let $x_1 \in X$ *be such that* $Qx_0 = Px_1$. Continuing this process, we can construct a sequence $\{\beta_n\}$in X such that $\beta_n = Px_n = Qx_{n-1}$, for all $n \ge 1$.

If $\beta_{n-1} = \beta_n$,for some $n \ge 1$ then $\beta_{n-1} = Px_{n-1} = Qx_{n-1}$

That is P and Q have a coincidence point x_{n-1}*in X Assume* $\beta_{n-1} \neq \beta_n$ for all $n \ge 1$. Then from (3.1.1)

$$d_E(\beta_{n-1},\beta_n) = d_E(Px_{n-1},Px_n) \ge \alpha_1 d_E(Qx_{n-1},Qx_n) + \alpha_2 d_E(Px_{n-1},Qx_{n-1}) + \alpha_3 d_E(Px_n,Qx_{n-1}) + \alpha_4 d_E(Px_n,Qx_n)$$
$$= \alpha_1 d_E(\beta_n,\beta_{n+1}) + \alpha_2 d_E(\beta_{n-1},\beta_n) + \alpha_3 d_E(\beta_n,\beta_n) + \alpha_4 d_E(\beta_n,\beta_{n+1})$$
$$\ge (\alpha_1 + \alpha_4) d_E(\beta_n,\beta_{n+1}) + \alpha_2 d_E(\beta_{n-1},\beta_n)$$

Which implies that

$$(1-\alpha_2) d_E(\beta_{n-1},\beta_n) \ge (\alpha_1 + \alpha_4) d_E(\beta_n,\beta_{n+1})$$

i.e. $(\alpha_1 + \alpha_4) d_E(\beta_n,\beta_{n+1}) \le (1-\alpha_2) d_E(\beta_{n-1},\beta_n)$

Or, $d_E(\beta_n,\beta_{n+1}) \le \frac{1-\alpha_2}{\alpha_1+\alpha_4} d_E(\beta_{n-1},\beta_n)$

Hence,

$$d_E(\beta_n,\beta_{n+1}) \le \alpha d_E(\beta_{n-1},\beta_n), \forall n \ge 1$$

Where, $\alpha = \frac{1-\alpha_2}{\alpha_1+\alpha_4} < 1$(as $\alpha_1 + \alpha_2 + \alpha_4 > 1$

By induction for all $n \ge 0$

$$d_E(\beta_n,\beta_{n+1}) \le \alpha^n d_E(\beta_0,\beta_1) \qquad (3.1.2)$$

Where $0 < \alpha < 1$

Using (3.1.1) and (3.1.2) and the facts that,

$$\alpha_1 \ge 2, \alpha_2 < 1, 0 < \alpha_3 < 1 \text{ and } 0 < \alpha_4 < 1$$

That is $\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 > 1$ *and* $0 < \alpha < 1$,

We have,

$$d_E(\beta_{n-1},\beta_{n+1}) = d_E(Px_{n-1},Px_{n+1})$$
$$\ge \alpha_1 d_E(Qx_{n-1},Qx_{n+1}) + \alpha_2 d_E(Px_{n-1},Qx_{n-1}) + \alpha_3 d_E(Px_{n+1},Qx_{n-1}) + \alpha_4 d_E(Px_{n+1},Qx_{n+1})$$
$$\ge \alpha_1 d_E(\beta_n,\beta_{n+2}) + \alpha_2 d_E(\beta_{n-1},\beta_n) + \alpha_3 d_E(\beta_{n+1},\beta_n) + \alpha_4 d_E(\beta_{n+1},\beta_{n+2})$$

Therefore,

$$\alpha_1 d_E(\beta_n,\beta_{n+2}) \le d_E(\beta_{n-1},\beta_{n+1}) - \alpha_2 d_E(\beta_{n-1},\beta_n) - \alpha_3 d_E(\beta_{n+1},\beta_n) - \alpha_4 d_E(\beta_{n+1},\beta_{n+2})$$
$$\le [d_E(\beta_{n-1},\beta_n) + d_E(\beta_n,\beta_{n+2}) + d_E(\beta_{n+2},\beta_{n+1})] - \alpha_2 d_E(\beta_{n-1},\beta_n)$$
$$-\alpha_3 d_E(\beta_{n+1},\beta_n) - \alpha_4 d_E(\beta_{n+1},\beta_{n+2})$$
$$\le d_E(\beta_n,\beta_{n+2}) + (1-\alpha_2) d_E(\beta_{n-1},\beta_n) - \alpha_3 d_E(\beta_{n+1},\beta_n)$$
$$+(1-\alpha_4) d_E(\beta_{n+1},\beta_{n+2})$$

Or,

$$\alpha_1 d_E(\beta_n,\beta_{n+2}) - d_E(\beta_n,\beta_{n+2}) \le (1-\alpha_2) d_E(\beta_{n-1},\beta_n) - \alpha_3 d_E(\beta_{n+1},\beta_n) + (1-\alpha_4) d_E(\beta_{n+1},\beta_{n+2})$$
$$(\alpha_1 - 1)\, d_E(\beta_n,\beta_{n+2}) \le (1-\alpha_2) d_E(\beta_{n-1},\beta_n) - \alpha_3 d_E(\beta_{n+1},\beta_n) + (1-\alpha_4) d_E(\beta_{n+1},\beta_{n+2})$$

Or,

$d_E(\beta_n,\beta_{n+2})$

$$
\begin{aligned}
&\le \left(\tfrac{1-\alpha_2}{\alpha_1-1}\right) d_E(\beta_{n-1},\beta_n) - \left(\tfrac{1-\alpha_2}{\alpha_1-1}\right) d_E(\beta_{n+1},\beta_n) + \left(\tfrac{1-\alpha_2}{\alpha_1-1}\right) d_E(\beta_{n+1},\beta_{n+2})\\
&\le \left(\tfrac{1-\alpha_2}{\alpha_1-1}\right) d_E(\beta_{n-1},\beta_n) - \left(\tfrac{\alpha_3}{\alpha_1-1}\right) d_E(\beta_n,\beta_{n+1}) + \left(\tfrac{1-\alpha_4}{\alpha_1-1}\right) d_E(\beta_{n+1},\beta_{n+2})\\
&\le \left(\tfrac{1-\alpha_2}{\alpha_1-1}\right) \alpha^{n-1} d_E(\beta_0,\beta_1) - \left(\tfrac{\alpha_3}{\alpha_1-1}\right) \alpha^n d_E(\beta_0,\beta_1) + \left(\tfrac{1-\alpha_4}{\alpha_1-1}\right) \alpha^{n+1} d_E(\beta_0,\beta_1)\\
&\le \left(\tfrac{1-\alpha_2}{\alpha_1-1} - \alpha\tfrac{\alpha_3}{\alpha_1-1} + \alpha^2\tfrac{1-\alpha_4}{\alpha_1-1}\right) \alpha^{n-1} d_E(\beta_0,\beta_1)\\
&\le \left(\tfrac{1-\alpha_2}{\alpha_1-1} - \tfrac{\alpha_3}{\alpha_1-1} + \tfrac{1-\alpha_4}{\alpha_1-1}\right) \alpha\alpha^{n-1} d_E(\beta_0,\beta_1)\\
&\le \left(\tfrac{2-(\alpha_2+\alpha_3+\alpha_4)}{\alpha_1-1}\right) \alpha\alpha^{n-1} d_E(\beta_0,\beta_1)\\
&\le \left(\tfrac{1+\alpha_1}{\alpha_1-1}\right) \alpha^n d_E(\beta_0,\beta_1)
\end{aligned}
$$

Hence,

$$d_E(\beta_n,\beta_{n+2}) \le \lambda\alpha^n d_E(\beta_0,\beta_1) \qquad (3.1.3)$$

For $\{\beta_n\}$we consider $d_E(\beta_n,\beta_{n+l})$ in two cases

If l is odd say 2p+1, for p≥ 1 then by using rectangular inequality and (3.1.2)

$$
\begin{aligned}
d_E(\beta_n,\beta_{n+2p+1}) &\le d_E(\beta_{n+2p+1},\beta_{n+2p}) + d_E(\beta_{n+2p},\beta_{n+2p-1}) + d_E(\beta_{n+2p-1},\beta_n)\\
&\le d_E(\beta_{n+2p},\beta_{n+2p+1}) + d_E(\beta_{n+2p-1},\beta_{n+2p}) + d_E(\beta_{n+2p-1},\beta_{n+2p-2})\\
&\quad + d_E(\beta_{n+2p-2},\beta_{n+2p-3}) + \cdots + d_E(\beta_{n+2},\beta_{n+1}) + d_E(\beta_{n+1},\beta_n)\\
&= d_E(\beta_n,\beta_{n+1}) + d_E(\beta_{n+1},\beta_{n+2}) + \cdots + d_E(\beta_{n+2p-1},\beta_{n+2p}) + d_E(\beta_{n+2p},\beta_{n+2p+1})\\
&\le \alpha^n d_E(\beta_0,\beta_1) + \alpha^{n+1} d_E(\beta_0,\beta_1) + \cdots + \alpha^{n+2p-1} d_E(\beta_0,\beta_1) + \alpha^{n+2p} d_E(\beta_0,\beta_1)\\
&\le [1 + \alpha + +\alpha^2 + \alpha^3 + \cdots]\alpha^n d_E(\beta_0,\beta_1)\\
&\le \tfrac{1}{1-\alpha}[\alpha^n d_E(\beta_0,\beta_1)]\\
&\le \tfrac{\alpha^n}{1-\alpha} d_E(\beta_0,\beta_1)\\
&\le \left[\lambda + \tfrac{1}{1-\alpha}\right] \alpha^n d_E(\beta_0,\beta_1)
\end{aligned}
$$

Hence,

$$d_E(\beta_n,\beta_{n+2p+1}) \le \left[\lambda + \frac{1}{1-\alpha}\right] \alpha^n d_E(\beta_0,\beta_1) \qquad (3.1.4)$$

For all $n \ge 1, p \ge 1, \lambda = \frac{1+\alpha_1}{\alpha_1-1} \ge 0$

If l is even say 2p for $p \ge 1$, then by using rectangular inequality(3.1.2), (3.1.3) and the fact that $0 < \lambda < 1$, we get

$$
\begin{aligned}
&d_E(\beta_n,\beta_{n+2p})\\
&\le d_E(\beta_{n+2p},\beta_{n+2p-1}) + d_E(\beta_{n+2p-1},\beta_{n+2p-2}) + d_E(\beta_{n+2p-2},\beta_n)\\
&\le d_E(\beta_{n+2p-1},\beta_{n+2p}) + d_E(\beta_{n+2p-2},\beta_{n+2p-1}) + \cdots + d_E(\beta_{n+3},\beta_{n+2}) + d_E(\beta_{n+2},\beta_n)\\
&= d_E(\beta_n,\beta_{n+2}) + d_E(\beta_{n+2},\beta_{n+3}) + d_E(\beta_{n+3},\beta_{n+4}) + \cdots + d_E(\beta_{n+2m-2},\beta_{n+2m-1})\\
&\quad + d_E(\beta_{n+2m-1},\beta_{n+2m})\\
&\le \lambda\alpha^n d_E(\beta_0,\beta_1)\\
&\quad + [\alpha^{n+2} d_E(\beta_0,\beta_1) + \alpha^{n+3} d_E(\beta_0,\beta_1) + \cdots + \alpha^{n+2m-2} d_E(\beta_0,\beta_1) + \alpha^{n+2m-1} d_E(\beta_0,\beta_1)]\\
&= \lambda\alpha^n d_E(\beta_0,\beta_1) + [\alpha^2 + \alpha^3 + \cdots + \alpha^{2m-1}]\alpha^n d_E(\beta_0,\beta_1)\\
&\le \lambda\alpha^n d_E(\beta_0,\beta_1) + [1 + \alpha + \alpha^2 + \alpha^3 + \cdots]\alpha^n d_E(\beta_0,\beta_1)\\
&\le \lambda\alpha^n d_E(\beta_0,\beta_1) + \tfrac{1}{1-\alpha}[\alpha^n d_E(\beta_0,\beta_1)]\\
&\le \lambda\alpha^n d_E(\beta_0,\beta_1) + \tfrac{\alpha^n}{1-\alpha}[d_E(\beta_0,\beta_1)]
\end{aligned}
$$

Hence,

$$d_E(\beta_n,\beta_{n+2p}) \le \left[\lambda + \tfrac{1}{1-\alpha}\right] \alpha^n d_E(\beta_0,\beta_1) \qquad (3.1.5)$$

For all $n \ge 1, m \ge 1$ *and*

$$\lambda = \frac{1+\alpha_1}{\alpha_1 - 1} \ge 0$$

From (3.1.4) and (3.1.5)

$$d_E(\beta_n,\beta_{n+l}) \le \left[\lambda + \frac{1}{1-\alpha}\right] \alpha^n d_E(\beta_0,\beta_1)$$

For all $n \ge 1, p \ge 1$ and $\lambda = \frac{1+\alpha_1}{\alpha_1-1} \ge 0$

Assume that $\theta \ll k$. Since,

$\alpha^n d_E(\beta_0, \beta_1) \to 0 \; as \; n \to \infty$

$\{\beta_n\}$ is a Cauchy sequence in X. since Q(X) is a complete subspace of X, then there exists a point $z \in$ Q(X) ⊆ P(X) such that

$\lim_{n\to\infty} \beta_n = \lim_{n\to\infty} Px_n = \lim_{n\to\infty} Qx_{n-1} = z$

Also we can find $x \in X$ such that z=PX.

Let $\theta \ll l$ be given, we can choose natural numbers $N_1 and\ N_2$ such that $d_E(z, \beta_{n-1}) \ll \frac{\lambda_1 l}{2(\lambda_1+1)}$

For all $n > N_1$ and $d_E(\beta_{n-1,}\beta_n) \ll \frac{l}{2}$

For all $n > N_2$. Let N= max $\{N_1, N_2\}$, from (3.1.1)

$$\begin{aligned} d_E(\beta_{n-1}, z) &= d_E(Px_{n-1,}Px) \\ &\geq \alpha_1 d_E(Qx_{n-1,}Qx) + \alpha_2 d_E(Px_{n-1,}Qx_{n-1}) + \alpha_3 d_E(Px_{,}Qx_{n-1}) + \alpha_4 d_E(Px_{,}Qx) \\ &\geq \alpha_1 d_E(\beta_{n,}Qx) + \alpha_2 d_E(\beta_{n-1,}\beta_{n,}) + \alpha_3 d_E(z, \beta_{n,}) + \alpha_4 d_E(z, Qx) \\ &\geq \alpha_1 d_E(\beta_{n,}Qx) \end{aligned}$$

Hence $d_E(\beta_{n,}Qx) \leq \frac{1}{\alpha_1} d_E(\beta_{n-1}, z)$

Using rectangular inequality

$$\begin{aligned} d_E(z, Qx) &\leq d_E(z, \beta_{n-1}) + d_E(\beta_{n-1,}\beta_{n,}) + \frac{1}{\alpha_1} d_E(\beta_{n-1}, z) \\ &\leq \left[1 + \frac{1}{\alpha_1}\right] d_E(\beta_{n-1}, z) + d_E(\beta_{n-1,}\beta_{n,}) \end{aligned}$$

Hence,

$$d_E(z, Qx) \ll \frac{l}{2} + \frac{l}{2} = l$$

i.e.

$d_E(z, Qx) = l$

Therefore

$Px = Qx = z$

That is, z is a point of coincidence of P and Q. if z^* is another point of coincidence of P and Q then

$P\gamma = Q\gamma = z^*$

For some $\gamma \in X$ then $d_E(z, z^*) = d_E(Px, Py)$

$$\begin{aligned} d_E(z, z^*) &\geq \alpha_1 d_E(Qx, Qy) + \alpha_2 d_E(Px, Qx) + \alpha_3 d_E(Py, Qx) + \alpha_4 d_E(Py, Qy) \\ &\geq \alpha_1 d_E(z, z^*) + \alpha_2 d_E(z, z) + \alpha_3 d_E(z^*, z) + \alpha_4 d_E(z^*, z^*) \\ &\geq (\alpha_1 + \alpha_3) d_E(z, z^*) \end{aligned}$$

Hence $d_E(z, z^*) \leq \frac{1}{(\alpha_1+\alpha_3)} d_E(z, z^*)$

Since, $\alpha_1 + \alpha_3 > 1$

Therefore, we have $d_E(z, z^*) = \theta$ i.e. $z = z^*$

P and Q have a unique point of coincidence in X.

Suppose P and Q are weakly compatible mappings, then we have

$Pz = PQx = QPx = Qz$

Therefore, $Pz = Qz = w(say)$

This shows that w is another point of coincidence between P and Q.

Therefore, by the uniqueness of the point of coincidence we must have $z = w$

Hence z is a unique common fixed point of P and Q in X.

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