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# Quasi-Cauchy Sequences on $\theta$-Parametric Metric Spaces

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**Abstract**− This paper proposes quasi-Cauchy sequences in $\theta$-parametric metric spaces, a generalized metric framework introduced by Moussaoui et al. in 2024. It establishes fundamental relationships among convergent, Cauchy, and quasi-Cauchy sequences, and puts forward concepts of ward compactness and ward continuity in $\theta$-parametric metric spaces. Moreover, the present paper demonstrates that ward continuity on a ward-compact subset in which every quasi-Cauchy sequence admits a convergent subsequence implies ordinary continuity, that uniformly continuous functions are necessarily ward continuous, and that uniform limits of ward-continuous functions preserve ward continuity. Consequently, all ward-continuous functions on $E$ form a closed set of continuous functions on $E$.

***Keywords*** − *Quasi-Cauchy sequences, parametric metric spaces, compactness*

## 1. Introduction

In recent years, the study of generalized metric structures has gained significant attention, particularly because they allow for the extension of classical notions of distance and continuity while preserving essential topological properties. Among these generalizations, the notion of $\theta$-metric spaces, first proposed by Khojasteh et al. [1], has played a prominent role by substituting the standard triangle inequality with a more adaptable condition governed by a $B$-action. Moreover, parametric metric spaces, such as parametric $A$-metric [2], parametric $S$-metric [3], and parametric soft $S$-metric spaces [4], introduce additional parameters or modifications to the classical distance function, thereby creating a richer analytical framework.

Subsequent developments in the theory of generalized metric spaces have produced several variants, including $b$-metric and parametric $b$-metric spaces, explored by Pasicki [5] and Hussain et al. [6], respectively, which further broaden the landscape of generalized metric spaces. Moreover, Moussaoui and Radenović [7, 8] provide an overview of $b$-metric-like and fuzzy metric spaces and their applications. Recently, Moussaoui et al. [9] unified these approaches by introducing $\theta$-parametric metric spaces, combining the axioms of both $\theta$-metrics and parametric metrics under a $B$-action framework. Similarly, Das and Bag [10] and Das et al. [11] investigated generalized $\theta$-parametric metric spaces by establishing topological and analytical properties, including convergence and Cauchy-type conditions.

Motivated by these advances, this study introduces and investigates quasi-Cauchy sequences in $\theta$-parametric metric spaces. Quasi-Cauchy sequences, studied initially in classical metric and normed spaces [12–14], allow for finer analysis of continuity and compactness-like properties. Forward continuity, a related concept that captures subtle sequential behavior, was investigated by [13, 15, 16]. From the perspective of $\theta$-parametric

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metric spaces, these sequences enable the extension of concepts such as ward compactness and ward continuity, capturing behaviors not detectable by standard Cauchy or convergent sequences.

This paper primarily explores the fundamental properties of quasi-Cauchy sequences in $\theta$-parametric metric spaces. It also investigates their relationships with classical Cauchy and convergent sequences, as well as the continuity notions that emerge from these generalized structures. Moreover, the present study demonstrate that ward continuity on a ward-compact subset in which every quasi-Cauchy sequence admits a convergent subsequence implies ordinary continuity and that uniform limits of ward-continuous functions maintain ward continuity. Finally, we prove that ward-continuous images of ward-compact sets are ward compact, thereby enriching the structural theory of these spaces. Overall, the results presented here provide a natural extension of existing work in both $\theta$-metric and parametric metric spaces and open new avenues for applications in nonlinear analysis, generalized compactness, and fixed point theory [1–6,9–11]. Beyond their role as a unifying framework, $\theta$-parametric metric spaces possess a rich structural flexibility arising from the interaction between the parameter component and $B$-actions. This flexibility allows for refined sequential and continuity concepts that extend beyond classical metric behavior. Therefore, studying quasi-Cauchy sequences in this setting generalizes existing results and reveals deeper structural aspects of generalized metric theory.

The rest of the paper is organized as follows: Section 2 presents basic definitions and preliminary results related to $\theta$-parametric metric spaces. Section 3 introduces quasi-Cauchy sequences in the considered framework and investigates their fundamental properties, including ward compactness and ward continuity. Moreover, this section studies the relationships between ward continuity, ordinary continuity, and uniform continuity, and investigates the behavior of ward-continuous functions under uniform convergence. The last section discusses the need for further research.

## 2. Preliminaries

This section introduces the basic concepts related to $\theta$-metric and parametric metric structures. These concepts provide the necessary foundation for the development of quasi-Cauchy sequences and ward continuity in the next section. Across this study, let $\mathbb{N}$ represent the set of all positive integers.

**Definition 2.1.** [1] Let $\theta : [0,\infty) \times [0,\infty) \to [0,\infty)$ be a function such that it is continuous in both arguments and $\mathrm{Im}(\theta) := \{\theta(a,b) : a,b \in [0,\infty)\}$. Then, the function $\theta$ is called a $B$-action if and only if the following hold:

*i.* $\theta(0,0) = 0$ and $\theta(a,b) = \theta(b,a)$, for all $a,b \geq 0$

*ii.* $\theta(a,b) < \theta(p,q)$ whenever either $a < p$ and $b \leq q$, or $a \leq p$ and $b < q$

*iii.* For all $s \in \mathrm{Im}(\theta)$ and each $a \in [0,s]$, there exists a $b \in [0,s]$ such that $\theta(b,a) = s$

*iv.* $\theta(a,0) \leq a$, for all $a > 0$

Through a $B$-action governing a parameterized metric, the framework of $\theta$-parametric metric spaces provides a common axiomatic generalization of both $\theta$-metric spaces and parametric metric spaces.

**Definition 2.2.** [9] Let $X \neq \emptyset$. A function

$$D_\theta : X \times X \times (0,\infty) \to [0,\infty)$$

is called a $\theta$-parametric metric on $X$ if the following conditions hold:

*i.* For all $x,y \in X$ and all $t > 0$,

$$D_\theta(x,y,t) = 0 \text{ if and only if } x = y$$

*ii.* For all $x, y \in X$ and all $t > 0$,

$$D_\theta(x, y, t) = D_\theta(y, x, t)$$

*iii.* For all $x, y, z \in X$ and all $t > 0$,

$$D_\theta(x, y, t) \leq \theta(D_\theta(x, z, t),\ D_\theta(z, y, t))$$

The pair $(X, D_\theta)$ is called a $\theta$-parametric metric space.

**Definition 2.3.** [9] Let $(X, D_\theta)$ be a $\theta$-parametric metric space and $\{x_n\}$ be a sequence in $(X, D_\theta)$. Then, $\{x_n\}$ is said to be convergent to a point $x \in X$ whenever, for each $\varepsilon > 0$, there exists an $n_0 \in \mathbb{N}$ such that $D_\theta(x_n, x, t) < \varepsilon$, for all $t > 0$, whenever $n \geq n_0$, and it is denoted by $x_n \to x$ as $n \to \infty$ or

$$\lim_{n\to\infty} D_\theta(x_n, x, t) = 0, \quad \text{for all } t > 0$$

**Proposition 2.4.** [9] Let $(X, D_\theta)$ be a $\theta$-parametric metric space. If the sequence $\{x_n\}$ in $X$ converges to a point $x \in X$, then $x$ is unique.

**Definition 2.5.** [9] A sequence $\{x_n\}$ in a $\theta$-parametric metric space $(X, D_\theta)$ is said to be a Cauchy sequence in $(X, D_\theta)$ if for all $t > 0$,

$$\lim_{n,m\to\infty} D_\theta(x_n, x_m, t) = 0$$

**Lemma 2.6.** [9] Let $(X, D_\theta)$ be a $\theta$-parametric metric space and $\{x_n\}$ and $\{y_n\}$ be sequences in $X$. If $\lim_{n\to\infty} x_n = x$ and $\lim_{n\to\infty} y_n = y$, then $\lim_{n\to\infty} D_\theta(x_n, y_n, t) = D_\theta(x, y, t)$, for all $t > 0$.

**Definition 2.7.** [9] Consider a $\theta$-parametric metric space $(X, D_\theta)$ with a mapping $G : X \to X$. Then, $G$ is called continuous at $x \in X$ whenever for each sequence $\{x_n\}$ in $X$ converging to $x$ as $n \to \infty$, the sequence $\{G(x_n)\}$ converges to $G(x)$ as $n \to \infty$.

## 3. Quasi-Cauchy Sequences in $\theta$-Parametric Metric Spaces

We define quasi-Cauchy sequences in the context of $\theta$-parametric metric spaces and study their properties. We begin by comparing quasi-Cauchy sequences with classical Cauchy and convergent sequences.

**Definition 3.1.** A sequence $\{x_n\}$ is called a quasi-Cauchy sequence in a $\theta$-parametric metric space $(X, D_\theta)$ if $\lim_{n\to\infty} D_\theta(x_{n+1}, x_n, t) = 0$, for all $t > 0$.

To illustrate the distinction between quasi-Cauchy and Cauchy sequences in $\theta$-parametric metric spaces, we present the following example.

**Example 3.2.** Let $X = \mathbb{R}$ and define

$$D_\theta(x, y, t) = \frac{|x - y|}{1 + t}$$

for all $t > 0$, where $\theta(a, b) = a + b$. Then, $(X, D_\theta)$ is a $\theta$-parametric metric space. Consider the sequence $\{x_n\} = \left\{\sqrt{n}\right\}$. Thus,

$$D_\theta(x_{n+1}, x_n, t) = \frac{|\sqrt{n+1} - \sqrt{n}|}{1 + t} \to 0 \quad \text{as} \quad n \to \infty$$

Hence, $\{x_n\}$ is a quasi-Cauchy sequence in $(X, D_\theta)$. However, $\{x_n\}$ is not a Cauchy sequence in $(X, D_\theta)$.

The following proposition describes a basic property of sequences in $\theta$-parametric metric spaces.

**Proposition 3.3.** If a sequence $\{x_n\}$ in a $\theta$-parametric metric space $(X, D_\theta)$ converges to $x \in X$, then every subsequence $\{x_{n_k}\}$ of $\{x_n\}$ converges to $x$.

Proof. Assume a sequence $\{x_n\}$ in $(X, D_\theta)$ converges to $x \in X$. Then, for all $\varepsilon > 0$ and all $t > 0$, there exists an $N \in \mathbb{N}$ such that for all $n \geq N$, $D_\theta(x_n, x, t) < \varepsilon$. Let $\{x_{n_k}\}$ be any subsequence of $\{x_n\}$. Since $n_k \to \infty$ as $k \to \infty$, there exists a $K \in \mathbb{N}$ such that $n_k \geq N$, for all $k \geq K$. Hence, for all $k \geq K$, $D_\theta(x_{n_k}, x, t) < \varepsilon$. Thus, $\{x_{n_k}\}$ converges to $x$. □

The following proposition presents how convergence is related to the Cauchy property in $\theta$-parametric metric spaces.

**Proposition 3.4.** Consider a $\theta$-parametric metric space $(X, D_\theta)$. If a sequence $\{x_n\}$ in $X$ converges to a point $x$ in $X$, then $\{x_n\}$ is a Cauchy sequence.

Proof. Because $\{x_n\}$ converges to $x$ in $X$, for all $\varepsilon > 0$, there exists an $N \in \mathbb{N}$ such that $n \geq N$ implies $D_\theta(x_n, x, t) < \varepsilon$ for all $t > 0$. Hence, whenever $n, m \geq N$,

$$D_\theta(x_m, x_n, t) \leq \theta(D_\theta(x_m, x, t),\ D_\theta(x_n, x, t)) < \theta(\varepsilon, \varepsilon)$$

Since $\theta$ is continuous in each variable, $\theta(\varepsilon, \varepsilon) \to 0$ as $\varepsilon \to 0$, and therefore for the chosen $\varepsilon$, $D_\theta(x_m, x_n, t) < \varepsilon$. Thus, $\{x_n\}$ is a Cauchy sequence. □

**Theorem 3.5.** Every Cauchy sequence in a $\theta$-parametric metric space $(X, D_\theta)$ is a quasi-Cauchy sequence.

Proof. Let $\{x_n\}$ be a Cauchy sequence in $X$. Then, for all $\varepsilon > 0$, there exists an $n_0 \in \mathbb{N}$, depending on $\varepsilon$, such that $D_\theta(x_n, x_m, t) < \varepsilon$ whenever $n, m \geq n_0$ and for all $t > 0$. In particular, taking $n = m + 1$, $D_\theta(x_{m+1}, x_m, t) < \varepsilon$, for each $m \geq n_0$. Hence, $\{x_n\}$ is a quasi-Cauchy sequence. □

Since every convergent sequence is a Cauchy sequence, it follows from the theorem above that every convergent sequence is a quasi-Cauchy sequence in $\theta$-parametric metric spaces. We introduce the compactness notion induced by quasi-Cauchy subsequences.

**Definition 3.6.** A $\theta$-parametric metric space $(X, D_\theta)$ is ward compact if every sequence in $X$ has a quasi-Cauchy subsequence.

By the ward compactness, we study functions that preserve quasi-Cauchy sequences.

**Definition 3.7.** Let $(X, D_\theta)$ be a $\theta$-parametric metric space and $E \subset X$. Then, a function $f : E \to X$ is ward continuous if it maps all quasi-Cauchy sequences $\{x_n\}$ in $E$ to a quasi-Cauchy sequence $\{f(x_n)\}$ in $X$.

The following theorem establishes that ward continuity implies ordinary continuity on ward-compact subsets of a $\theta$-parametric metric space.

**Theorem 3.8.** Let $E$ be a ward-compact subset of $(X, D_\theta)$ such that every quasi-Cauchy sequence in $E$ has a convergent subsequence. Then, every ward-continuous function $f : E \to X$ is continuous on $E$.

Proof. Let a sequence $\{x_n\}$ in $E$ converge to $x_0 \in E$. Then, $\{x_n\}$ is a quasi-Cauchy sequence. Since $f$ is ward continuous, $\{f(x_n)\}$ is a quasi-Cauchy sequence. By the assumption, $\{f(x_n)\}$ has a convergent subsequence $\{f(x_{n_k})\}$ converging to some $y$. Because $x_{n_k} \to x_0$ and limits are unique in $\theta$-parametric metric spaces by Proposition 2.4, $y = f(x_0)$. Hence, every subsequence of $\{f(x_n)\}$ has also a subsequence converging to $f(x_0)$. Therefore, $f(x_n) \to f(x_0)$, which proves continuity of $f$ at $x_0$. □

We then investigate compactness under ward-continuous mappings.

**Theorem 3.9.** Consider a $\theta$-parametric metric space $(X, D_\theta)$ and a ward-continuous function $f : X \to X$. Then, every ward-compact set is mapped to a ward-compact set.

Proof. Assume that $(X, D_\theta)$ is a $\theta$-parametric metric space, $f : X \to X$ is ward continuous, and $E \subset X$ is a ward-compact set. Consider a sequence $\{x_n\}$ in a subset $E \subset X$, and suppose that $\{y_n\}$ is a sequence in $f(E)$ such that $f(x_n) = y_n$, for all $n$. Since $E$ is ward compact, there exists a subsequence $(z_k) = (x_{n_k})$ satisfying $\lim_{k\to\infty} D_\theta(z_{k+1}, z_k, t) = 0$, for all $t > 0$. Define $l_k = f(z_k)$. The sequence $\{l_k\}$ is a subsequence of $\{y_n\}$. Because $f$ is ward continuous, $\lim_{k\to\infty} D_\theta(l_{k+1}, l_k, t) = 0$, for all $t > 0$. Consequently, every sequence in $f(E)$ has a quasi-Cauchy subsequence. Hence, $f(E)$ is ward compact. □

We investigate how uniform continuity relates to ward continuity.

**Definition 3.10.** Let $(X, D_\theta)$ be a $\theta$-parametric metric space and $E \subset X$. A function $f : E \to X$ is said to be uniformly continuous on $E$ if for all $\varepsilon > 0$, there exists a $\delta > 0$ such that for all $x, y \in E$ and all $t > 0$,

$$D_\theta(x, y, t) < \delta \Rightarrow D_\theta(f(x), f(y), t) < \varepsilon$$

**Theorem 3.11.** Suppose $(X, D_\theta)$ is a $\theta$-parametric metric space and $f : X \to X$ is a function. If $f$ is uniformly continuous over a subset $E \subset X$, then it is ward continuous over $E$.

Proof. Suppose $(X, D_\theta)$ is a $\theta$-parametric metric space, $f : X \to X$ is uniformly continuous over a subset $E \subset X$. Let $\{x_n\}$ be a quasi-Cauchy sequence. Then, using uniform continuity of $f$, for all $\varepsilon > 0$, there exist a $\delta > 0$, determined by $\varepsilon$, such that for all $t > 0$, $D_\theta(f(x), f(y), t) < \varepsilon$ whenever $D_\theta(x, y, t) < \delta$. Corresponding to this $\delta > 0$, for each $t > 0$, there exists an $N \in \mathbb{N}$ such that $D_\theta(x_{n+1}, x_n, t) < \delta$ whenever $n > N$ . Thus, for every $t > 0$, $D_\theta(f(x_{n+1}), f(x_n), t) < \varepsilon$ whenever $n > N$. Hence, the sequence $\{f(x_n)\}$ is a quasi-Cauchy sequence. Consequently, $f$ is ward continuous over $E$. □

The following theorem studies how ward continuity is preserved under uniform convergence.

**Theorem 3.12.** Let $(X, D_\theta)$ be a $\theta$-parametric metric space and $E \subset X$. If $\{f_n\}$ is a sequence of ward-continuous functions on $E$ and $f_n \to f$ uniformly on $E$, then $f$ is ward continuous on $E$.

Proof. Suppose that $\{f_n\}$ is a sequence of ward-continuous functions on $E$ such that $f_n \to f$ uniformly on $E$. Let $\{x_n\}$ be a quasi-Cauchy sequence in $E$. By uniform convergence, for all $\varepsilon > 0$, there exists an $N_1 \in \mathbb{N}$ such that $D_\theta(f_n(x), f(x), t) < \varepsilon$, for all $x \in E$, $t > 0$, and $n \geq N_1$. Because $f_{N_1}$ is ward continuous, there exists an $N_2 \in \mathbb{N}$ such that $D_\theta(f_{N_1}(x_{n+1}), f_{N_1}(x_n), t) < \varepsilon$, for all $t > 0$ and all $n \geq N_2$. Thus, for $n \geq N = \max\{N_1, N_2\}$,

$$D_\theta(f_N(x_n), f(x_{n+1}), t) \leq \theta\Big(D_\theta(f_N(x_n), f_N(x_{n+1}), t), D_\theta(f_N(x_{n+1}), f(x_{n+1}), t)\Big) < \theta(\varepsilon, \varepsilon)$$

and

$$D_\theta(f(x_{n+1}), f(x_n), t) \leq \theta\Big(D_\theta(f(x_{n+1}), f_N(x_n), t), D_\theta(f_N(x_n), f(x_n), t)\Big) < \theta(\theta(\varepsilon, \varepsilon), \varepsilon)$$

Taking limit as $\varepsilon \to 0$ in the above inequalities and using the fact that $\theta$ is continuous with respect to each variable, $\lim_{n\to\infty} D_\theta(f(x_{n+1}), f(x_n), t) = 0$, for all $t > 0$. Hence, $\{f(x_n)\}$ is a quasi-Cauchy sequence in $E$ and $f$ is ward continuous on $E$. □

**Theorem 3.13.** Let $(X, D_\theta)$ be a $\theta$-parametric metric space and $E \subset X$. Then, the set of all ward-continuous functions on $E$ is topologically closed in the space of continuous functions on $E$.

Proof. Suppose that $\{f_n\}$ is a sequence of ward-continuous functions on $E$ which converges uniformly to a function $f$. Let a sequence $\{x_m\}$ in $E$ be a quasi-Cauchy sequence. Then, $\lim_{m\to\infty} D_\theta(x_{m+1}, x_m, t) = 0$, for all $t > 0$. By uniform convergence, for all $\varepsilon > 0$, there exists an $N \in \mathbb{N}$ such that $D_\theta(f_N(x), f(x), t) < \varepsilon$, for all $x \in E$ and all $t > 0$. Because $f_N$ is ward continuous,

$$\lim_{m\to\infty} D_\theta(f_N(x_{m+1}), f_N(x_m), t) = 0$$

Thus, for sufficiently large $m$,

$$D_\theta(f_N(x_m), f(x_{m+1}), t) \leq \theta\Big(D_\theta(f_N(x_m), f_N(x_{m+1}), t), D_\theta(f_N(x_{m+1}), f(x_{m+1}), t)\Big) < \theta(\varepsilon, \varepsilon)$$

and

$$D_\theta(f(x_{m+1}), f(x_m), t) \leq \theta\Big(D_\theta(f(x_{m+1}), f_N(x_m), t), D_\theta(f_N(x_m), f(x_m), t)\Big) < \theta(\theta(\varepsilon, \varepsilon), \varepsilon)$$

Taking limit as $\varepsilon \to 0$ in the above inequalities and using the fact that $\theta$ is continuous with respect to each variable, $\lim_{m\to\infty} D_\theta(f(x_{m+1}), f(x_m), t) = 0$, for all $t > 0$. Hence, $\{f(x_m)\}$ is a quasi-Cauchy sequence, and $f$ is ward continuous on $E$. Consequently, the set of all ward-continuous functions on $E$ is closed. □

## 4. Conclusion

This paper investigates quasi-Cauchy sequences in the framework of $\theta$-parametric metric spaces, thereby developing ward compactness and ward continuity in this generalized setting. Rather than merely extending classical definitions, the study demonstrates that $\theta$-parametric metric spaces provide a flexible and structurally rich environment in which sequential behavior can be analyzed beyond standard notions of Cauchy and convergent sequences. The results indicate that ward continuity is structurally compatible with classical continuity under suitable compactness-type assumptions and behaves well with respect to uniform approximation. These findings suggest that quasi-Cauchy-based continuity concepts are naturally adapted to the $B$-action structure underlying $\theta$-parametric metric spaces. Moreover, this study highlights the broader analytical potential of $\theta$-parametric metric spaces. Since these spaces unify $\theta$-metric and parametric metric frameworks, they offer a powerful setting for reinterpreting compactness, convergence, and continuity in a more general context. The rich interaction between the parameter component and $B$-action mechanism enables the refinement of sequential tools that may not be visible in classical metric theories. Future research may focus on alternative convergence types in $\theta$-parametric spaces, deeper compactness structures, and applications to fixed-point theory, nonlinear analysis, and other models formulated in generalized metric spaces. Exploring these directions can further clarify the structural role of $\theta$-parametric metrics within the broader theory of generalized distance spaces.

## Author Contributions

The author read and approved the final version of the study.

## Declaration

This study is not derived from any thesis or dissertation.

## Conflicts of Interest

The author declares no conflict of interest.

## Ethical Review and Approval

No approval from the Board of Ethics is required.

## Artificial Intelligence (AI) Use Statement

The author declares that no artificial intelligence (AI) tools were used in the conception, design, or generation of the main/original results of this study, including data collection, analysis, or interpretation. AI tools were used only for editing assistance, such as improving language, readability, or reference formatting. The author is solely responsible for the content, accuracy, and integrity of the study.

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